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The Effectiveness of Commercially Available Wetting Agents for Combating On-Site Soil Water Repellency in Sandy Soil

"A report submitted to the School of Science And Engineering, Murdoch University in partial fulfillment of the requirements for the degree of Bachelor of Engineering"

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Abstract

Soil hydrophobicity reported to be a worldwide problem throughout the world and Australia affecting diverse soil types particularly soil with high sand content. Soil hydrophobicity affect surface and subsurface hydrology, enhance overland flow and soil erosion, reduce seed germination and crop growth, cause preferential flow and associated leaching of nutrients and agrochemicals. The cause of soil water repellency is believed to be organic coating of the soils particles result from breakdown of organic substances such as; plant roots, fungal or microbial by-products. The most common method of managing soil water repellency in urban areas is application of wetting agents most of which are surfactant based. A trial was conducted at Murdoch University to test the efficacy of three leading locally available commercial wetting agent products and their effect on three commercially available pre-mixed landscape soils. Results from capillary rise, WDPT and double ring infiltrometer tests suggest that; application of selected wetting agents not only did not result in enduring improvement in soil wettability, but also in some cases appear to enhance soil water repellency. These observations lead to the hypothesis that; surfactant molecules in the wetting agents bond to soil particles in the same way as organic hydrophobic materials that coat the soil grains. To substantiate the results, further investigation required to understand the mechanism by which wetting agent molecules interact with soil particles.

Acknowledgements

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1 Introduction

Soils that repel water or do not easily absorb water are hydrophobic. Soil hydrophobicity reported to be a worldwide problem throughout the world and Australia affecting diverse soil types particularly soils with high sand content (Karnok and Beall 1995). Some of the major environmental reproductions of water repellent soil comprise; enhanced overland flow, which can lead to flooding and soil erosion, reduction in seed germination and crop growth; enhanced preferential flow and associated leaching of nutrients and agrochemicals and poor performance of amenity turf (Doerr *et al.* 2000). The cause of soil water repellency is believed to be organic coating of the soils particles result from breakdown of organic substances such as; plant roots, fungal or microbial by-products (Karnok and Beall 1995 and Leinaurer 2002).

Accelerating expansion of population and demand on usable land and water resources has lead to increasing interest in improving irrigation efficiency and distribution of water uniformly through the soil. Therefore, there is increasing interest in developing methods of managing soil hydrophobicity as a mean of improving the irrigation efficiency. One of the most common strategies for alleviating soil water repellency in urban areas considered to be the application of wetting agents most of which are surfactant based (Gross *et al.* 2010). Wetting agents are detergent-like substances which theoretically allow water penetrate and wet the soil more easily (Leinaurer 2002). Various types of wetting agents are being developed and many have been promoted strongly by the Western Australia State water provider, nursery garden industry and horticultural media. However, the effectiveness of wetting agents on various soil types requires further investigation. In respond, a trial to investigate the efficacy of wetting agents has been conducted at Murdoch University.

The aim of this study is to evaluate the effectiveness of three commercially available; surfactant, mineral and humus based wetting agents to ameliorate soil water repellency, in three sandy based soils. The specific objectives of this study are to:

- Evaluate the changes in capillary rise of sand and landscape mixes following application of humus, mineral and surfactant based wetting agents.
- Evaluate the effect of the wetting agents on the infiltration to the sand and landscape mixes.
- Correlate results of capillary rise and infiltration test to the (water droplet penetration test) WDPT method which is the most commonly practiced method for evaluation of water repellency in the field.

2 Literature Review

Soil water repellency is a widespread phenomenon with major retroactions for plant growth, surface and subsurface hydrology and for soil erosion (Doerr *et al.* 2000 and Poulter 2006). Advances have been made in; identifying the affects of soil water repellency on environment, methods for measuring soil water repellency as well as strategies in remediation of soil water repellency. This review aims to provide background information in; mechanism, cause and affects, methods of measurements and remediation of soil water repellency.

2.1 Soil Water Repellency

It is generally assumed that dry soils are rapidly and uniformly moistened under rainfall or irrigation; however, not all soils display these wettable characteristics, but repel water (DeBano 1981). Soil water repellency (SWR) or hydrophobicity is characteristic of some soils in which soil particles do not easily absorb water or mix with it (Mangual *et al.* 2009). In other word, hydrophobic soils absorb little or no water (Bachmann 2004) and cause water to sit on the soil in beads, reducing the infiltration rate of water into the subsurface and unstable water flow within the soil matrix (Resurreccion *et al.* 2010 and Jonge *et al.* 1999).

2.2 Occurrence of Soil Water Repellency (Hydrophobicity)

Soil hydrophobicity often recognized in surface layer of the soils that dries out frequently (Dekker *et al.* 1998). In most cases water repellency does not extend deeper than the top 5 cm of the soil and on rare occasion it may be found as deep as 10 cm or more (Karnok 2003). According to Jaramillo *et al.* (1999) soil hydrophobicity is more common in dry climates and rare in humid climates. Similar theory has been cited in a review by Doerr *et al.* (2000) which states; ‘‘soils are most repellent when dry and least repellent or non-repellent (hydrophilic) when moist’’. In contrary, Hallet (2007) states that; water repellency has been also detected in unlikely environment of Scotland. Leinauer *et al*. (2003) also suggests that; water repellency is strongest in soils with low clay content and when soil dries. Conversely, Bisdom *et al.* (1992), express that in fact many surface layers of sandy as well as clayey and peaty soil can exhibit slight to extreme hydrophobic characteristic when dry. Leelamanie *et al.* (2008) articulates that; the occurrence of soil hydrophobicity in terms of physical and chemical properties of the soil and water as follow; ‘‘under natural condition, water repellency appears on low-energy surfaces where the attraction between the molecules of the solid and liquid interface is weak’’.

Soil hydrophobicity is widespread throughout the world and Australia (De Jonge *et al.* 1999). It has been estimated that; soil hydrophobicity affect more than 5 million hectares of sandy soils in agricultural land in south Western Australia, from Geraldton to east of Esperance and in south-eastern Australia on Eyre Peninsula and in a region south of Adelaide extending to western Victoria (Roper 1999).

Soils of the Swan Coastal Plain in Perth in Western Australia are typically characterised as being coarse sands with low moisture holding capacity (Gross *et al*. 2010). Thus, soil form this region expected to exhibit hydrophobic characteristic. Soil hydrophobicity is also a common feature of both naturally occurring and modified sandy soils in the regions (Blackwell 1996). Soils with smaller surface areas found in WA gardens as well as bagged potting mixes and bulk landscape soils are more prone to water repellency as it takes less hydrophobic material to coat individual particles, compared to silt or clay (Karnok and Tucker 2002).

2.3 Mechanism of Water Movement into Soil and Soil Hydrophobicity

Before discussing the cause of soil water repellency (SWR), it is important to describe the mechanism of water movement through soil by firstly explaining physical properties and characteristics of water and soil. However, materials covered here are closely linked to the cause of hydrophobicity which will be discussed in 1.4.

Water is imbalanced polar (dipole) molecule (Cantoria 2011) consisting of hydrogen and oxygen molecules linked with hydrogen bonding (Capri 2003). Physical property of water can be explained by attractions (cohesion) force and repellent (adhesion) force between polar water molecules imposed by its polarity. Cohesion force creates water surface tension and capillary action and adhesion force cause water to spread out or cling to other materials e.g. as soil grains (Poulter 2003).

Theoretically, when water comes into contact with soil surface an attraction between the soil and water molecule occurs. For water to infiltrate into soil, adhesion force in water molecules must exceed cohesion force (Aquastrols Surfactant Technology 2010). In many literatures gravitational and capillary forces are considered as primary factors in movement of water into soil. For instant; Watson *et al.* (1995) and Hallett (2007) describe that; movement of water into soil (infiltration of water into soil) is due to gradients in water content or gravity. Watson *et al. (*1995) also append that; capillary force cause water to move laterally in unsaturated soil and gravity cause downward water movement in saturated soil.

Soil chemical and physical characteristic are also important when describing factors in water movement into soil. Bouma, *et al*. (2003) defines soil structure as the physical constitution of soil materials in various size, shape and arrangement of the soil particles composed of mineral and organic particles with pores (voids) in between. Several cited literatures (Watson *et. al.* 1995; Bisdom *et al.* 1993; Salma *et al.* 2001; Hallett 2007; Slay 2007 and Roper 1999) listed; soil texture, structure, water content, water holding capacity, organic matter and bulk density as key factors in water infiltration into soil and soil hydrophobic characteristic.

Soil's pore structure plays an important role in flow characteristics of water and solutes in soil (Lipiec *et al.* 2006). Doerr (2007) describes that; any porous materials such as soil draw water when attraction between a water molecule and the material is stronger than attraction between individual water molecules. Similar concept has been articulated in a number of literatures; Pidwirny (2006); Poulter (2003); Ball (2001) and Lipiec *et al.* (2006), in which soil porosity has been described as a key factor in water infiltration into soil and controlled by soil texture, structure, and organic content.

In terms of texture and pore size, soil generally is classified as coarse (soil sand or loamy sand), medium (soil is a loam and silt loam) and fine soil (sandy clay, silty clay, or clay). Coarse soils have lighter and larger particles and larger pores, but less overall pore space, thus, allow for more water flow (Pidwirny 2006) but have less water holding capacity (ball 2001). In contrast, fine soils have heavier and smaller grains and smaller pores, but larger surface area and overall pores space, therefore allow slower water movement, but have greater water holding capacity (Kopec 1995). Dynamic of flow through porous materials in particular soils is a complex concept which is out of scope of this paper. However, in simple terms, this can be explained by the function of capillary and gravitational force in soil. Soils with lower pore space (sandy soil) become saturated faster and are influenced more by gravitational force, therefore have faster infiltration rate. On the other hand, soils with more pore space (clayey soil) are more influence by unsaturated flow and grater capillary force, thus have lower water movement and lower infiltration rate (Menenti *et al.* 2007 and Beven and Germann 1982).

2.4 Cause of Soil Water Repellency (Hydrophobicity)

The cause of soil hydrophobicity and formation of water repellent soil have been subject to many studies. Generally; soil texture, climate, plant species and cover density are considered as some of the contributing factors in formation of hydrophobic soil and its severity and distribution (DeBano 1981). According to McGhee and Posner (1981) a number of plant species can cause formation of soil water repellency namely citrus trees, various chaparral brush species and shrub trees. However, most literatures such as in Wolfgang *et al.* (2007) and Bisdom *et al.* (1992), listed; high temperature, low soil water content, high humus content and presence of hydrophobic materials and soil fungi are listed as key factors causing soil hydrophobicity. As indicated in these literatures, both physical and chemical soil properties as well as environmental factors are potential contributor to formation of hydrophobic soil.

Soil water content or soil moister level has been considered as another important contributing factor in soil water repellency in various cited literatures (De Jongel *et al.* 1999; Karnok and Tucker 2002 and Poulter 2003). Soil water content and water holding capacity is controlled by the several forces mainly molecular force of elements and compounds found on the surface of soil minerals (Pidwirny 2006). Attempt has been made to establish a critical soil moisture threshold to differentiate between the water repellent and non-repellent conditions (Doerr and Thomas 2000). Soil water repellency has been explained and examined in terms soil moisture threshold or critical point in several literatures. For instant, Poulter (2003) and Leighton-Boyce *et al.* (2005) suggest; when moisture is above the soil critical point or soil moisture threshold, water repellency effect is temporarily eliminated and when soil moisture falls below this point, soil becomes hydrophobic.

However, according to Karnok and Tucker (2002) “the reported thresholds are vary widely and the exact relationship between hydrophobicity and soil moisture remains far from being understood ’’. Study conducted by Doerr and Thomas (2000) indicated that; for the particular soil subject to their study, soil hydrophobicity was absent when the soil moisture level was above the critical point/threshold. In the same study Doerr and Thomas (2000) also demonstrated that; water repellency did not re-establish when soil became dry again, as suggested in other literatures. This result contradicts the theories in relation to the importance of soil moisture critical point in soil water repellency.

Soil hydrophobicity considered to be the consequence of formation of hydrophobic substances around the soil grains (Salma *et al*. 2001; Roper 1999 and DeBano 1981). Theoretically these hydrophobic substances have non-polar section which repel water molecules and cause the soil to become hydrophobic (Ritsema and Dekker 1994; Karnok and Tucker 2004). According to Poulter (2006), it takes as little as 3 to 6 % hydrophobic materials in the soil matrix to cause non-wetting problems. Conversely, presence of hydrophobic compounds does not necessarily always cause soil water repellency (Leelamanie *et al.* 2008). Result of study by Bisdom and Dekker (1993) also demonstrated that, a combination of soil constituents and coatings with organic matters found to be the cause of SWR. Furthermore, water repellent soil has also been linked with populations of basidiomycete fungi and actinomycetes in soil (Roper 1999). For example; Karnok and Tucker (2002) suggest that, presence of thick fungal mycelia may prevent the movement of water into the soil and cause soil to become water repellent.

In Salma *et al.* (2001), Hallett (2007) and several other literatures, the main cause of soil hydrophobicity have been attributed to the coating of the sand particles with a skin of organic material. In contrary, Pidwirny (2006), states that; decayed organic matter found at the soil surface can in fact enhance water infiltration and subsequently reduce soil hydrophobicity. Pidwirny (2006) justified his statement by explaining that; organic matters are generally more porous than mineral soil particles and can hold greater quantities of water, hence increase soil water infiltration rate. The function of soil porosity in water infiltration has been noted previously. Conversely, in another article, Doerr (2007) suggest that; soil consists of minerals and organic materials which may or may not attract water depending on its chemical composition and structure. Nevertheless, majority of cited literatures, e.g. Bisdom *et al.* (1993); Poulter (2006); Salma *et al.* (2001); Hallett (2007) and Ritsema and Dekker (1994) considered organic coating of soil grains as an important factor in soil hydrophobicity.

Generally, organic materials coating soil particles are complex waxy compounds which form during the decomposition of organic matters. In a review by DeBano (1981) irreversible drying of organic matters and plants by fire described as a factor in formation of organic coating on soil grain. Similarly, Slay (2007) and Roper (1999) also list major sources of organic matters in soils as; decomposed plant roots, fungal or microbial by-products which coat soil particles and render the soil hydrophobicity. These organic matters assumed to form a part of soil structures (e.g. micro- and macro-aggregates) or be the principal component itself (Bisdom *et al.* 1992).

In addition to decomposed plant and fungal or microbial by-products, oil, grease and surfactant in graywater (used for irrigation) are other sources of organic matters which potentially contribute to soil hydrophobicity. Reuse of gray water for irrigation as a mean of water conservation has taken on increasing interest in recent years. The result of investigation by Travis *et al.* (2008) demonstrated that; organic components in greywater can accumulate in soil irrigated with greywater and may lead to a significant reduction in soils ability to transmit water.

Although oil and grease are present in all streams, but greywater from the kitchen is reported to be the highest contributor of oil and grease in domestic greywater (Friedler 2004). In the similar study by Travis *et al.* (2008) it was demonstrated that; long-term greywater-irrigated soils exhibited oil and grease concentrations similar to those irrigated with greywater with high concentration oil and grease, can significantly reduce imbibitions of water into the soil and trigger soil hydrophobicity. Furthermore, irrigation using insufficiently treated greywater can cause accumulation of surfactants and sodium in present in untreated greywater and cause soil hydrophobicity (Shafran *et al.* 2006).

2.5 Effects of Soil Hydrophobicity

Soil water repellency has typically been related to dry and sandy soils with major ramification for plant growth, surface and subsurface hydrology, and for soil erosion (Doerr *et al.* 2007). However, SWR affects diverse soil types and as noted previously, it is a widespread occurrence affecting millions of hectares of mostly dry soils throughout the world and Australia (Roper 1999; Kostka *et. al.* 2007; DeBano 2000 and Ritsema *et al.* 2003). Karnok *et al.* 2001) also describes the extend of soil hydrophobicity and articulate that; soil water repellency affects agricultural lands and forests as well as sand base gardens, grasslands and golf greens. Consequences of soil hydrophobicity are listed in an article by Poulter (2006) as follow; drainage and leaching of nutrients, runoff, and uneven distribution of applied chemicals and localized Dry Spot (LDS). Furthermore, Feng *et al.* (2001); Wallis *et al.* (1991) and Wallis and Horne (1992), included; the effect on evaporation rate and hydraulic balance to the list of affects of soil hydrophobicity.

Soil hydrophobicity in turf and grassland causes uneven water distribution in the soil profile. This can translate into “dry patches” (Poulter 2003), which often referred to as; local dry spots (LDS) or isolated dry spots, dry patch or hot spots (Karnok and Tucker 1999). Karnok and Tucker (2001) defined local dry spots as occurrence of an irregular area of turfgrass that exhibit signs of typical drought stress. According to Wolfgang *et al.* (2007), high temperature, low soil water content, high humus content and presence of soil fungi trigger soil hydrophobicity and leads to LDS in grassland.

Soil hydrophobicity increase surface run off and soil the susceptibility to erosion in a variety of ways such as increased aggregate stability, reduced infiltration capacity, enhanced overland flow (Shakesby *et al.* 2000). According to an article by the Department of Crop and Soil Sciences Oregon State University (2007) soil water repellency cause uneven infiltration which also referred to as preferential flow, can lead to water runoff and subsequently cause soil erosion. In extreme rain events accelerate runoff on hydrophobic soil and cause flood (Slay 2007). Logsdon *et al.* (2008) articulated that; in rain event, water do not infiltrate into water repellent soil and pond on the surface and if there is any micro-macro topographical contours, then water flow to the lower depressions. This leads to surface run off and subsequently topsoil erosion.

The success of forestry practice also can be affected by runoff and soil erosion of soil resulted from the water repellent soil. Usually, fire and intense burn in forestry may induce the formation of water repellency from development of humus and its related microorganisms. As previously noted; presence of these hydrophobic materials contributes to soil hydrophobicity which promote excessive run-off and erosion in a burned area and subsequently affect relations between soil water and plants (DeBono *et al.* 1973).

Soil water repellency also can considerably affect agricultural productivity by significantly reduce crop and pasture establishment and production (Wang *et.al;* 2000 and Roper 2005). As noted previously, soil water repellency accelerates soil erosion, this result in loss of fertile top soil where water repellency is expected (Letey 2001; DeBano 1981; Doerr 2007; Poulter 2003 and Leelamanie *et al.* 2007). Crops and pastures grown on water repellent soils often suffer from poor germination and low yields. This result in poor plant cover, which consequently can predispose the soil surface to wind and water erosion (Zolfaghari and Hajabbasi 2008). Several literatures (DeBoano 1981; Doerr 2007 and Wessel 1988) also articulated that; soil water repellency affects plant and crops establishment by reducing the water available for germination and growth. In addition, water repellent soil induces overland flow which carries the plant seeds before they germinate.

Surface and groundwater water hydrology can be affected by soil hydrophobicity. According to Dekker and Ritsema (1994) ‘’Water repellent soils often show irregular moisture patterns, which lead to accelerated transport of water and solutes and nutrient to the groundwater and surface water (Doerr *et al.* 2000). Water repellency also affects the way in which rainwater penetrates the soil, thereby inducing preferential flow paths (Zolfaghari and Hajabbasi 2008). Consequently, water and solutes can reach the water-table more rapidly than in the case of a homogeneous infiltration front and consequently affect the quality of the groundwater (Zolfaghari and Hajabbasi 2008; Dekker and Ritsema 1994 and Doerr *et al.* 2000).

2.6 Methods of Testing Soil Hydrophobicity

Several methods for measuring the severity of soil water repellencey have been developed over the years. Wallis and Horne (1992) and Leelamanie *et al.* (2008) have listed a number of these methods such as; water drop penetration time (WDPT) test, capillary rise method (CRM), molarity of an ethanol droplet (MED) test, the ninety-degree surface tension method, infiltration, intrinsic sorptivity and diffusivity, and thermal analysis. However, the most commonly used methods of assessing the degree of soil water repellency in literature are including; water droplet penetration test (WDPT), infiltration rate test, capillary rise test, Morality of Aqueous Ethanol Droplets (MED).

According to Mangual *et al.* (2009); DeBano (1981) and several others, water droplet penetrations time is the most commonly use and simplest method of determining the degree of soil water repellencey under field and laboratory conditions by measuring the time it takes for a water drop to penetrate into soil (DeBano 1981 and Roy and McGill 2002). This method is particularly used for assessing the water repellency in LDS. WDPT involve taking approximately 2 cm of field-moist or dried samples. Then, placing a water drop on the surface of soil sample measure the time it takes for the water drop to penetrate into soil (King 1981 and Poulter 2006). To increase the test accuracy it is best to record several measurements on each sample. However, reliability of prediction of soil water repellency may decreases as the area of sampling increases (McKissock *et al.* 1998).

The qualitative data obtained from WDPT can be classified into categories according to test's objectives and the perception of the investigator. However, several literatures (Micheal *et al.* 2008, Poulter 2003; Bisdom *et al*. 1993 and King 1981) presented WDPT threshold to distinguish between wettable and water repellent soils. According to Doerr *et al.* (2007) one of the widely used water repellency classes for the WDPT test are those listed in table 1, which also have been referred to in; Chenu *et al*. (2000), Throssell (2005) and King (1981).

Table 1 Repellency categories with corresponding water drop penetration times (WDPT) (Bisdom *et al*. 1993; Chenu *et al*. 2000; King 1981 and Throssell 2005)

WDPT (s)	Repellency category
≤ 1 s	Non-repellent
1–60 s	Slightly repellent
60–600 s	Strongly repellent
600–3600 s	Severely repellent
≥ 3600 s	Extremely repellent

As noted previously, capillary rise test is another common method of measuring soil water repellency. Liquids capillary rise in soil column controlled by the capillary force as discussed previously in “movement of water into soil” section. This method is based on measuring the capillary rise of a liquid or selected test solution, in a dry column of packed soil or granular material (lately *et al.* 1962 in Leelamanie *et al.* 2008). Three fundamental physical characteristics related to capillary rise are; the maximum height of capillary rise, the fluid storage capacity of capillary rise, and the rate of capillary rise (Lu and Likos 2004).

Capillary rise test as described in Wiel-Shafran *et al.* (2006) and several other litretuers, involves placing dry soil sample into columns/cylinder which covered by fine mesh at the bottom. The cylinder then attached to a stand placed on a balance. An open reservoir containing water or solution according to the test then rose underneath the bottom of the soil column. The capillary rise force causes the liquid to rise into soil. The balance attached to a data logger which set to record the weight of the solution raised in the soil Column every few second. This method has been outlined in Wiel-Shafran *et al.* (2006), and Leelamanie *et al.* (2008). Figure 1, illustrates the capillary rise test experimental set up.

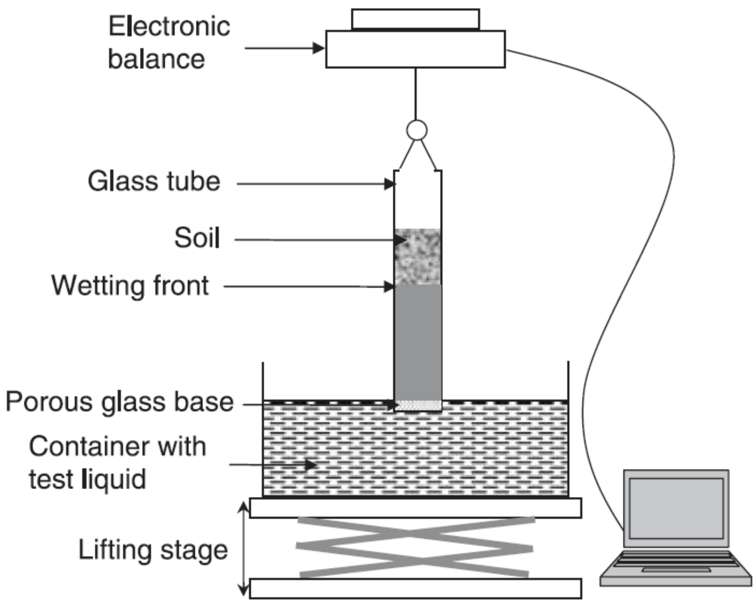

Figure 1. Experimental setup for the capillary rise method (Leelamanie *et. al.* 2008**)**

Infiltration rate test is another commonly used method of determining the degree of soil water repellency. As it has been discussed previously in ''movement of water into soil'' section, infiltration of water in soil or downward water movement into soil is primarily controlled by gravitational force. There are several methods of measuring infiltration rate which vary in their accuracy and complexity. One of the relatively simple, accurate and commonly used approach is the ring infiltrometer method. This method is involved in inserting a ring into the soil. Then, water is poured into the ring and the rate at which the water penetrates into the soil is measured.

Gregory *et al.* (2005) states that; in single-ring infiltrometer method the vertical infiltration rate may be overestimated. To overcome the error and increase accuracy of the infiltration test, other methods such as double infiltrometer have been developed. According to Lai and Ren (2007) double infiltrometer method is commonly used to evaluate the saturated hydraulic conductivity of the surface layer of the soils. The procedure in double infiltrometer is similar to the single ring infiltrometer method except that in this method another larger but equal length infiltrometer ring is inserted into soil adjacent the smaller ring as illustrated in figure 2.

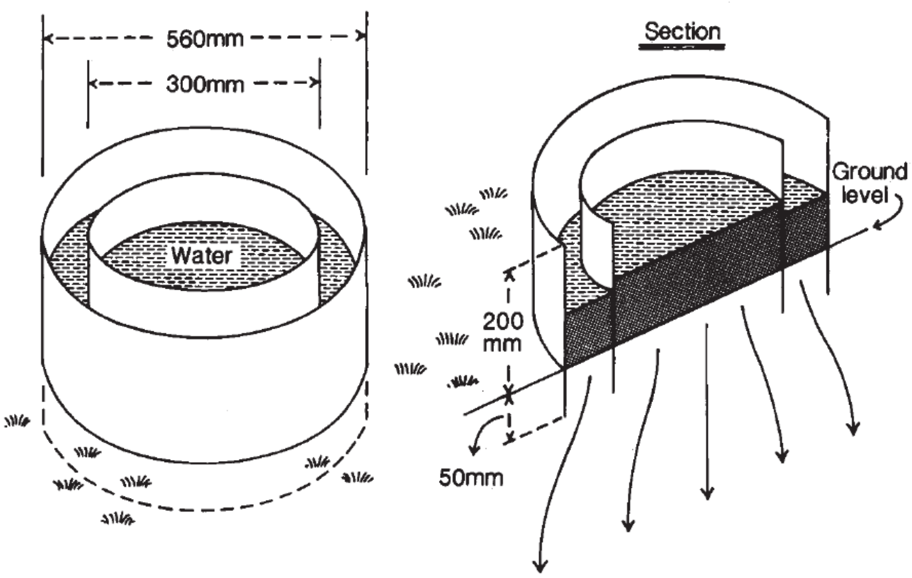

Figure 2. Double ring infiltrometer and its cross section.

2.7 Methods of Alleviating Water Repellent Soils

Various strategies have been developed to ameliorate water repellency. According to Ma'shum *et al.* (1989); Blackwell (1993) and Ward (1993), one of the most successful of these is the use of kaolinite clays. This method works by simply increasing the clay content in hydrophobic soil assuming it can be evenly distributed through the soil. However, this method may not be economic and practical due to the large quantity of clay required particularly if the clay do not occurs on sit and must be brought from other locations (Roper 2004).

Other relatively less practiced method of alleviating water repellent soil is using wax-degrading bacteria to increase microbial activity by wax-degrading bacteria in soil. Result of study in Roper (2004) indicated that; increase soil wettability by using wax-degrading bacteria likely to be more practical and economic alternative to other more expensive strategies such as wetting agents or claying.

Cultivation is also one of the common strategies to manage soil water repellency. Orfanus *et al.* (2010) state that; presence of residual after-fertilization carbonates can enlarged the hydrophilic/hydrophobic surface ratio and increase pH which result in increase overall soil hydrophobicity. Result of study by Orfanus *et al.* (2010) demonstrated that; cultivation can reduce the effect of residual after-fertilization carbonates and partly alleviate arable soil water repellency.

The most common management approaches to alleviate soils water repellency cited in literatures (Thorssell 2005; Karnok *et al.* 2004; Laha *et al.* 2000; Kostka 2000, Cisar *et al.* 2000) are including; application of surfactants (wetting-agents) and frequent irrigation scheduling to avoid the soil surface zone drying out. Drying accentuates the movement of organic solutes to soil surfaces and if water content is reached to critical point, a water repellent barrier can form (Wallis and Horne 1992; Ritsema and Dekker 1996). However, according to Thorssell (2005); “in long term, these practices are of lower preference due to latent environmental risks from broad application of wetting agents, and the impracticality of frequent watering during a water resource scarcity’’.

Application of wetting agents particularly surfactants base wetting agents is one of the most common practices for managing soil water repellency Generally, wetting agent work by lowering water surface tension and allow it to wet the waxy surface of the soil particles and improve the water penetration into soil (Karnok *et al.* 2004, Fisher 1942 and Leinauer 2002).

2.8 Wetting Agents

As noted in Thorssell (2005), Karnok *et al.* (2004); Laha *et al.* (2000); Kostka (2000); Cisar *et al.* (2000) and several other literatures, wetting agents are used as the most common strategy to alleviate soil water repellency. According to Gross *et al.* (2010), wetting agents are also strongly promoted by the Western Australia State water provider, nursery garden industry and horticultural media as the most effective method of eradicating soil water repellency.

Generally, soil wetting agents are available in liquid and granular form and various formulas and mainly surfactant based. The granular forms are best for potting mixes and liquid wetting agents are good for larger areas such as garden beds. Furthermore**,** Illingworth (2000) listed the most commonly promoted wetting agents in Australia as; anionic and non-ionic surfactants, polymeric non-ionic surfactants, medium term polymeric wetting agent, eco friendly wetting agents, fairway wetting agents, humectants and granules wetting agents. For the purpose of this paper, surfactant based wetting agents will be further discussed.

2.9 Surfactant Based Wetting and How They Work

Theoretically, wetting agent particularly surfactant based wetting agents improve water infiltration into soil by decreasing water molecular cohesive forces or in other word water surface tension and allow it to wet the waxy surface of the soil particles and improve water penetration into soil (Karnok *et al.* 2004; Fisher 1942 and Leinauer 2002).

Wetting agents belong to a class of chemicals referred to as surfactants. The word surfactant as described in Lee *et al.* (2002) is an abbreviation for 'surface active agent,' so named because these molecules tend to migrate to surfaces and interfaces or create new molecular surfaces by forming aggregates'.

As previously discussed, soil hydrophobicity is the consequence of formation of hydrophobic substances around the soil grains (Salma *et al*. 2001; Roper 1999 and DeBano 1981). As illustrated in figure 3, these hydrophobic materials theoretically have non-polar section such as humic acids and plant waxes around soil grains which repel water (Ritsema and Dekker 1994; Karnok and Tucker 2004). Water is a dipole molecule consists of two hydrogen atoms and one oxygen atom. In contrast, a typical wetting agent or surfactant is an amphiphilic molecules with a polar/ hydrophilic head which also referred to as water soluble group and a non-polar/lipophilic end which usually referred to as oil-soluble usually hydrocarbon chain (Karnok *et al.* 2004 and Lee *et al.* 2002). When wetting agent is applied to the soil, as illustrated in figure 4, the non-polar end of wetting agent molecules attracts the hydrophobic materials coating on soil grain and its polar head attracts water molecules to soil grains (Karnok *et al.* 2004). As long as there is sufficient wetting agent bonding with the organic coating, the soil or sand particle is not expected to be water repellent (Karnok and Tucker 2004).

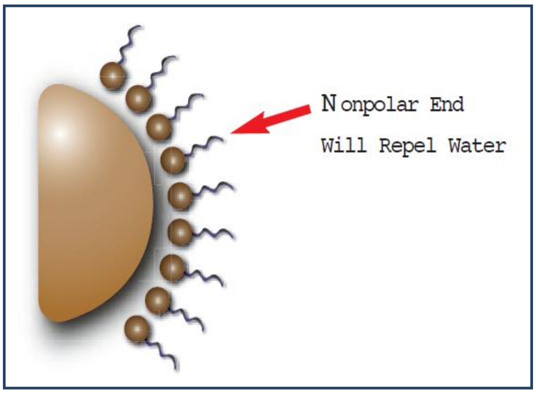

Figure 3. Diagram of soil particle with a water-repellent organic coating.

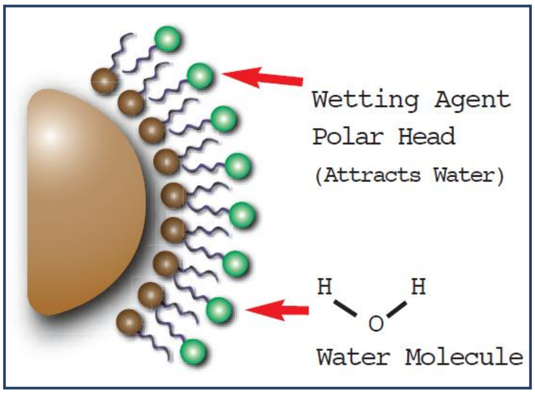

Figure 4. Diagram of a soil particle with a water-repellent organic coating after treatment with wetting agent.

2.10 Studies on Efficacy of Wetting Agents

Wetting agents are marketed in various form and formulation and differ significantly in their ability to reduce soil water repellency. Evaluating the efficiency of wetting agents has been subject to numerous studies. Result of some of these studies can be reviewed in Park *et al*. (2004); Pelishek *et al.* (1962); DeBano (1967); Karnok and Tucker (2001); Leinauer (2002); Pelishek *et al*. (1962) and others.

One example is the study conducted by DeBano *et al.* (1967) to determine the effectiveness of wetting agent on water repellent burned watershed soil in southern California. The soil hydrophobicity in this area has been linked to the vegetation and soil temperature during fire. The result of this study indicated that; application of wetting agent helped retard debris and improved vegetation which indicated the effectiveness of the wetting agent. However, Letey *et al.* (1962) suggested that; "one wetting agent on the market may be superior for one problem or soil type, whereas another product may be superior for another set of conditions'' Letey *et al.* (1962) also recommended that to select the best product for different cases more detailed investigation is necessary on the physical-chemical interaction between the wetting agent molecule and soil particle surface.

Result of another study conducted in South Florida by Park *et al.* (2004) demonstrated that; properly timing and frequent applications of a surfactant at a low rate has been effective in reducing SWR symptoms. Park *et al.* (2004), also suggests that; warm temperature and intense rain in South Florida creates an optimal environment for microbial decomposition, soil re-wetting, and leaching of surfactants which influence soil exhibit hydrophobic symptoms. Similar study conducted in the University of Georgia Rhizotron, Athens, GA in 1997 and 1998 indicated an improvement in infiltration rate into soil as a result of application of wetting agents (Karnok and Tucker 2001).

Another interesting study conducted by Pelishek *et al.* (1962) demonstrated that; application of a wetting agent can improve the infiltration rate in a hydrophobic soil, but it has either no effect or adverse affect on non water repellent soils. Furthermore, the wetting agent used in the study produced a beneficial residual effect and did not completely leached from thatch.

Attempts have been made to explore other potential benefits of using wetting agents. For instance, result of a study conducted in California State University, Pomona, demonstrated that; wetting agents can be used as a tool for water conservation and reducing stress on plants (Mitra *et al.* 2003).

There are also studies which demonstrated the adverse effects of application of wetting agents. For instance, result of study conducted by Leinauer *et al.* (2007) demonstrated that; some wetting agents not only did not improved soil wettability but also increased soil water repellency. In a different study it was demonstrated that; coating of sand by anionic and nonionic surfactants resulted in enhanced water repellency (Wiel-Shafran *et al.* 2005). The same study also showed that even at low concentration of 10 mg/kg of anionic and nonionic surfactants significant water repellency was observed. Other study conducted by Abu-Zreig *et al.* (2003) indicated similar results for higher surfactant concentrations (i.e. ~3000 mg/L). In the same study it was observed that; the applications of anionic and non ionic surfactants caused decreases in the capillary rise and penetrability of water to sandy loam soil.

Overall, most of studies indicated that wetting agents have been effective in reducing soil water repellency or enhancing soil wettability to some degree. However, it is important to consider factors such as; variation in wetting agents formulas, soil types and degree of soil hydrophobicity as well as environmental factors which may contribute to the efficiency of a wetting agent in any given situation. In addition, most cited literature indicated that the efficiency of wetting agents was tested on dry or burned soil. According to De Jongel *et al.* (1999), water repellency is dependent on soil water content, thus, performing the WR test solely on dry soils can lead to the wrong classification regarding whether a soil is water repellent or not. Thus, it is important to consider the result of tests using different techniques to achieve more accurate result (De Jongel *et al*. 1999).

3 Materials and Methods

The trial was conducted under controlled conditions at Murdoch University Western Australia during summer 2011. The efficacy of the three commercially available liquid wetting agents were tested by assessing their continuous effect on; infiltration rate tests, capillary rise, water droplet penetration tests (WDPT) and infiltration of water into the different soils mixes.

Three leading commercially available liquid wetting agents selected and used in this trial are including;

1. Surfactant based wetting agent
2. Mineral based wetting agent
3. Humus based wetting agent

Scheme water is used in all control tests (a set of soil sample replicates that only have been tested/treated with water) to obtain reference data. Data from control test are compared with data obtained from experiments with wetting agents to evaluate the efficiency of the wetting agents.

Three commercially available pre-mixed landscape soils were selected for this trial are as follow;

1. Landscape Mix by Amazon (L)
2. Aquasoil by Amazon (A)
3. Clean quarry sand supplied by Amazon (control) (S)

These pre-mixed landscape soils are usually used in gardening in Western Australia.

3.1 Capillary Rise Experiment

The effect of selected wetting agents on capillary rise was determined on soil subsamples according to laboratory procedure suggested by Wiel-Shafran *et al.* (2006). To conduct the experiment under controlled condition oven dried and burnt soil was prepared from each soil type. Soil was dried in the oven to reduce the soil moisture content and burned in furnace high to eliminate organic matters in soil.

To prepare oven dried and burned soil for capillary test, approximately 60kg of each soil type was sieved using a 2.0-mm sieve. 30kg of each representative soil samples dried in the oven at approximately 100°C for the period of at least 24 hours. To prepare burned soil, 30 kg of each soil types was burnt in a muffle furnace at approximately 600°C for about 4 hours and cooled in room temperature.

Each soil samples either oven dried and burned soil was placed and thoroughly packed in polypropylene columns up to 240ml. Dimension of polypropylene columns used were; internal Ø 38mm x length 295mm. The bottom of soil column was covered with a fine mesh net to allow solution raise to the soil column.

Three replicates of each soil type Aquasoil, Landmix and Sand (A, L and S) oven dried and three replicates of each soils (Ab, Lb and Sb) burned soils were prepared for each stages of capillary test with each wetting agent solution and water as control solution. For instance, for testing each soil with water as control test, 3xA+3xL+3xS=9 soil replicates for oven dried soil and, similarly three replicates of each burned soils 3xAb+3xLb+3xSb=9 thus, a total of 18 soil samples were prepared for capillary rise test with water as rising solution for control test. Similarly 3 replicates of L, S and A as well as Lb, Sb and Ab (a total of 18 samples) were prepared for capillary test with each wetting agent solution.

To conduct capillary rise test, the soil column was attached to a stand and placed on a balance (AND, or every model GF-2000) as shown in figures 5 and 6. An open reservoir containing freshwater (control) or a wetting agent solution (prepared according to the manufacturer’s instruction) was raised beneath the column until the water surface touched the bottom of the column. Being a measure for water repellency, capillary rise was assessed as the weight of water rising in the column registered by the balance as a change in mass. The weight change due to the capillary rise of the tested solution in the columns was recorded with a data logger connected to the balance. Data logger was set to record the weight of water raised in the column once every five seconds. Each capillary test was carried out for 30 minutes.

The first capillary rise test was control test, using scheme water as rising solution. Three soil replicate from each soil (a total of 18 soil columns) was tested with water. Once the capillary rise stopped as indicated by no change in weight over time, the columns were dried in the oven at 100^{0}C for 24 hours. Previous experiments showed that; capillary rise usually stops at approximately 30 minutes for this size of soil columns. Therefore, all the capillary tests in this trial conducted for 30 minutes for each replicate. After soil dried in the oven the Capillary rise test were repeated on these dry samples using water as rising solution. This procedure was considered to represent common irrigation practice in gardens and detect the changes in capillary rise when soil is only irrigated with scheme water. Result of this test provided a reference (control test) which was used to compare other capillary rise tests using wetting agents.

Capillary rise test was similarly repeated on each soil replicate but this time using wetting agents as rising solution. Wetting agent solutions were prepared according to manufacture instruction. Once the capillary rise stopped at approximately 30 minutes, the soil columns were dried in the oven at 100^{0}C for 24 hours. The columns were cooled to room temperature and another capillary rise experiment was repeated on each soil (treated with wetting agents and dried) column using scheme water as the rising solution. This procedure was considered to imitate the common practice of the irrigation using a wetting agent followed by irrigation with scheme water without the wetting agent.

Figure 5. Illustration of the capillaries experimental set-up.

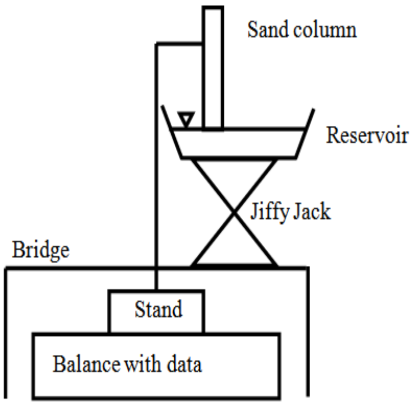

Figure 6. Schematic diagram of capillary rise experimental set up.

3.2 Water Droplet Penetration Test (WDPT)

Water Droplet Penetration Test (WDPT) was conducted on each oven dried and burned soil to as a mean of estimating the degree of soil water repellency. To prepare soil for this experiment, approximately 500g of each burned and oven dried were prepared in the same way as described for capillary rise tests. Approximately 100 g of each soil types both oven dried and burned were placed in a small aluminum pie dish. Four replicate for each soil type were prepared for each soil type as follow; soil Ax4 (100g each), Soil Lx 4 (100g each) and soil Sx4 (100g each), similarly for burned soil; Abx4 (100g each), Lbx4 (100g each) and Sbx4 (100g each), so in total there were 24 soil samples from all soils.

Using a water droplet, a drop of water was placed randomly on soil surface as shown in figure 7, and the time it took for the drop of water to penetrate into soil was measured using a stopwatch and recorded. The test was repeated at least 8 times in each sample to obtain sufficient data to estimate the average time of water penetration into soil.

The WDPT was repeated on soil samples treated with wetting agents according to following procedure. Approximately 500ml of each wetting agent was prepared according to manufacture instruction for preparation of each wetting agent. 100g of each soil type (sample) saturated with 50ml of wetting agent solution. After adding wetting agent each sample should weight 150g (100g soil +50ml wetting agent solution). Similarly, soil for control tests, 100g of each soil treated/saturated with 50ml scheme water. All samples treated with wetting agents or scheme water were placed in the oven at 100°C for 24 hours and cooled in room temperature. WDPT was repeated on treated and dried soils samples and data were recorded to compare with first WDPT and the WDPT control test.

Figure 7. Water Droplet Penetration Test (WPDT), LH: burned sand; RH: oven-dried sand

3.3 Infiltration Rate Test

Infiltration rate test using infiltrometer particularly double ring infiltrometer is a commonly used method of evaluating the saturated infiltration rate in soils (Lai and Ren 2007). Approximately 700kg of each three selected soil types; Aquasoil (A), Landmix (L) and Sand (S) were sieved using 2cm sieve. Approximately 50L of each soil type were placed in 65L plastic barbells (65 L, inner Ø42 cm x height 47 cm) so that there were 12 soil barrels of each soil type. There barrels of each soil types were allocated to each wetting agent and three barrels of each soil type were allocated for control test which were only treated with scheme water. To compact the soils, barrels were shaken after each soil load was introduced in the barrel.

Into each of the barrels two plastic double ring infiltrometer were inserted concentrically 10 cm deep into the soil with minimum soil disturbance as illustrated in figure 8. The heights of both rings were 20cm and outer and inner ring diameters were 17 and 8.3 cm respectively. 20mm from the inner edge of the inner rings were marked using permanent marker. This is to measure the infiltration rate of solution into soil from 0 to 20mm. Alternatively, a ruler could be placed inside the inner ring to measure the change in height of the water when conducting infiltration test. The soil barrels were situated outside, under cover protected from rain.

Figure 8. Infiltration test experimental set up. LH; soil barrels; RH; double ring infiltrometer

Initially, to further compact the soil, the infiltration rate of all barrels was measured by the double ring infiltrometer technique using scheme water. To measure the initial infiltration rate, the outer infiltrometer ring field with water after which the inner ring was filled to a level equivalent to an initial 70-80 mm head. The time taken for the water level in the inner ring to drop to 20 mm (as marked) was recorded using a timer. Thereafter, a measured volume of water that is equivalent to 20 mm in depth in the ring was filled successively and the time taken to infiltrate this amount was recorded. The measurement was taken at least 8 times. When the amount of water entering into the soil did not change much with time for 5 consecutive measurements, steady-state flow was assumed and the average infiltration rate was calculated (based on these last 5 measurements). Water level in the outer ring was maintained after this initial infiltration measurement, soil was left to dry for 7 days.

Wetting agents were prepared according to the manufacturer's instructions on the product. Each type of wetting agent then applied to 3 soil barrels of each soil type allocated to a wetting agent. Scheme water was applied to 9 barrels, 3 barrels of each soil, as control test. After this treatment soil barrels were left to dry for 7 days.

Infiltration rate were re-measured with scheme water on all barrels. This procedure was conducted to mimic common irrigation practice of large pots. Differences of the percent reduction among treatments at each date were tested by analysis of variance.

4 Results and Discussion

The conceptual approach in this trial was to evaluate the efficiency of three commercial wetting agents by studying their affect on capillary rise, WDPT and infiltration rate on three commercially prepared soil mixes.

4.1 Sand and Wetting Agents

Figure 9; illustrates the result of capillary rise tests on oven-dried sand before and after treatment with wetting agents and treatment with water in control test. Solid lines represent the capillary rise of wetting agents in oven-dried sand and dotted lines represent the capillary rise of water in oven-dried sand treated with wetting agents. Blue solid and dotted lines represents the capillary rise of water in control test.

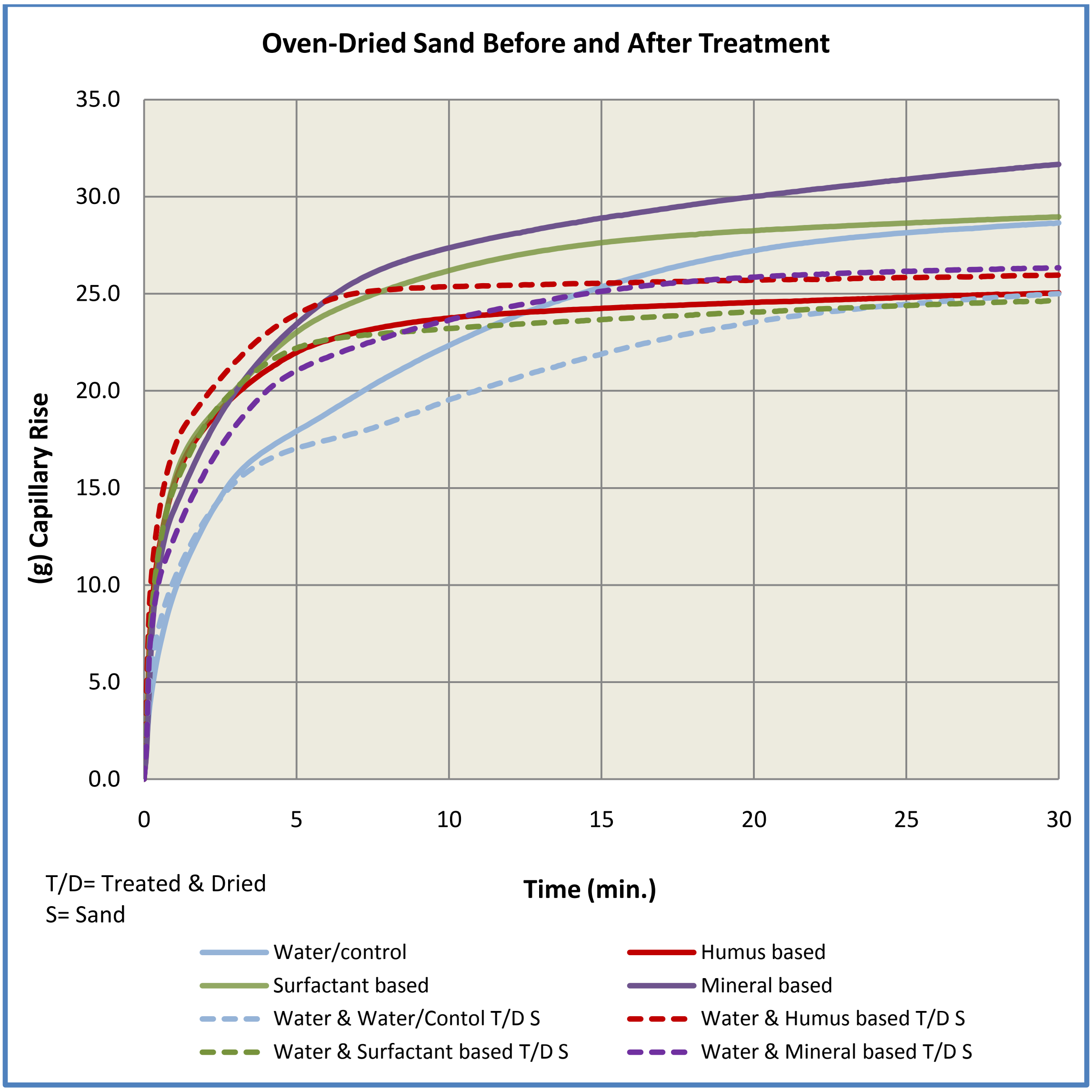

Figure 9. Result of capillary rise of wetting agents and water (control test) in oven-dried sand and result of capillary rise of water in oven-dried sand treated with wetting agents and water (control test).

Result demonstrated that; the effect of different wetting agents on oven-dried sand are vary and minimal compare to capillary rise of water in oven-dried sand. The rate of capillary rise of wetting agents in first 15 minutes of the test was approximately 20% higher than water rise, but the differences gradually reduced after 30minuts. The capillary rise of water after 30 minutes was almost the same as rise of surfactant based wetting agent, 10% lower than mineral base and 12% higher than humus based wetting agent rise. Variation in capillary rise is mainly due to the way each wetting agent and water molecules interact with soil hydrophobic materials.

Graph shows a reduction in capillary rise of water on all treated sand except for the sand treated with humus based wetting agent. A reduction of 20%, 15% and 15% were observed in capillary rise of water in treated sand with mineral based, surfactant based wetting agent and water respectively. Conversely, there was an approximately 3% increase in capillary rise of water in sand treated with humus based wetting agent. There also seemed to be a grater reduction in capillary rise of water in sand treated with mineral based and surfactant based wetting agents compare to rise of water in water-treated sand. Results demonstrated that; the affect of wetting agents in enhancing capillary rise did not last after treated sands were dried. This indicated that; the wetting agents may have contributed to soil hydrophobicity. On the other hand, capillary rise of water also has reduced in sand treated with water. This indicated the contribution of water treatment and drying process in enhancing sand water repellency.

The standard deviations of capillary rise tests of water in oven-dried sand before and after treatment are less than 5% and the standard deviation of wetting agents in burned landmix before and after treatment are less than 10%. This indicates minimal variations between the values of the capillary rise for each soil replicate.

Figure 10; illustrate the capillary rise in burned sand before and after treatment with wetting agents and water in control test. Solid lines represent the capillary rise of wetting agents in burned sand and dotted lines represent capillary rise of water on burned sand treated with wetting agents. Solid and dotted blue lines indicate the capillary rise of water in control test.

As expected, the capillary rise of wetting agents and water in burned sand was higher than in the oven-dried sand, demonstrating the contribution of organic matter to the sand hydrophobicity.

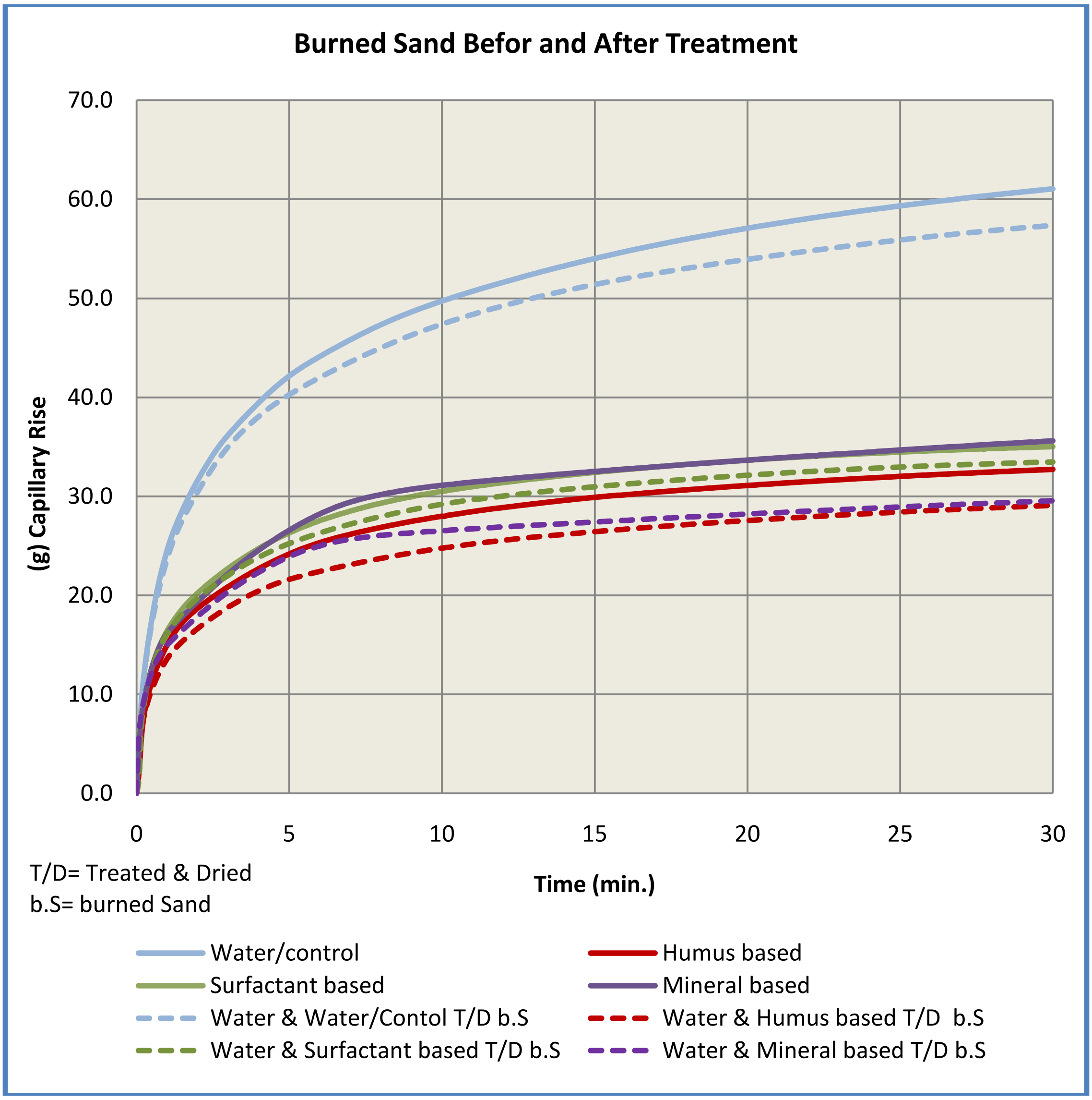

Figure 10. Result of capillary rise of wetting agents and water (control test) in burned sand and result of capillary rise of water in burned sand treated with wetting agents and water (control test).

Capillary rise of water in burned sand (control test) was 55% higher than capillary rise of wetting agents in burned sand. The capillary rise of wetting agents in burned sand was almost the same and approximately 50 to 55% lower than water rise in control test. Burned sand does not contain organic materials thus; capillary rise is mainly controlled by water surface tension. The significant difference in capillary rise of water and wetting agents in burned sand indicated the effect of wetting agents in reducing water surface tension and subsequent reduction in capillary rise compare to water.

Approximately 7 to 10% reduction in capillary rise of water in all treated burned sand was observed. However, the decrease in capillary rise of water in sand treated with mineral based wetting agent was more than the decrease in capillary rise of water in control test and capillary rise of water in burned sand treated with humus and surfactant based wetting agents. As the capillary rise in burned soil is mainly controlled by water surface tension, it was expected that the capillary rise increase after sand treated and dried, but the result indicated otherwise. Decrease in capillary rise of water in all treated burned sand (control test and sand treated with wetting agents) is an indication of formation of hydrophobicity in burned sand due to the application of wetting agents and water (control test) and drying process.

The standard deviations of capillary rise tests of water in burned sand before and after treatment are less than 7% and the standard deviation of wetting agents in burned sand before and after treatment are less than 18%. This indicated minimal variations between the values of the capillary rise in control test and slightly higher variations in capillary rise in soil replicates which treated with wetting agents.

Infiltration rate test was conducted as explained in method section previously. Data collected in all stages of infiltration test have been converted to meter/day, normalized and summarized in figure 11. All the blue bars represent infiltration rate of water in sand control test. The first set of column represent the infiltration rate of water into sand before application of wetting agents and third and fourth set of columns represent the infiltration rate of water into sand after application of wetting agents.

As illustrated in graph, application of mineral based and surfactant based wetting agents improved the infiltration rate by approximately 5 to 3% where as application of humus based wetting agent and water (control test) reduced the infiltration rate by 8 and 5% respectively compare to initial irrigation of soils with water.

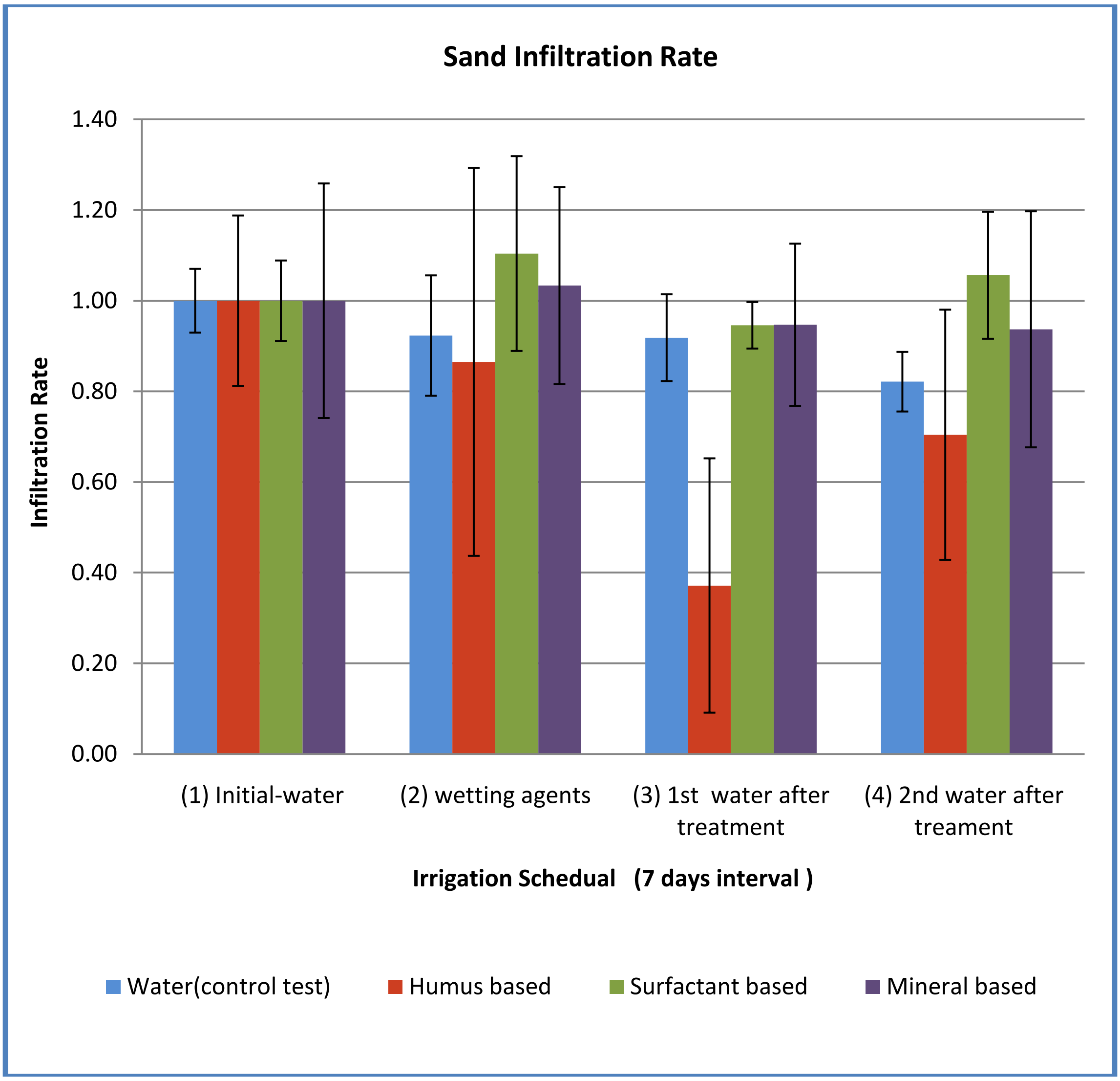

Figure 11. Infiltration rate of wetting agents; humus based, surfactant based and mineral based and water in control test in sand. (1) initial irrigation with water on all sand barrels, (2) application of wetting agents and water in control test, (3) first irrigation after treatment, using water in all sand barrels (4) second irrigation after treatment, using water on all soil barrels.

The first irrigation using water after treatment (application of wetting agents and water in control test) and drying period also did not show any improvement in average infiltration rate compare to initial irrigation with water and at the time of application of wetting agents. In fact, the infiltration rates of water in sand treated with humus based wetting agent has reduced by 50% compare to infiltration rate at the time of application of the wetting agent and was 60% lower compare to infiltration rate of water into sand treated with water in control test. However, the infiltration rate of water into sand in first irrigation after treatment was approximately 10% lower for all treated soils with surfactant based, mineral based wetting agents or water (control test) compare to initial irrigation with water. As indicated in the graph, only application of surfactant based wetting agent seemed to improve the infiltration rate by an average of 12% compare to application of water in control test in all stages of the test.

The temporarily affect of wetting agent could be due to reduction in water surface tension at the time of application of wetting agents and the reduction in infiltration after treatment could be due to formation of hydrophobicity after application of wetting agent and drying process. However, for more accurate assessment, the variations in standard deviations of infiltration rate measurement must be taken into account. For instance, a large variation in standard deviation observed in infiltration rate of sand treated with humus based wetting agent can be explained by the natural variation of water repellency in sand. Also, variation observed during and after sand was treated with wetting agent can be due to preferential flow caused by wetting agent.

Overall, result demonstrated that; the application of wetting agents did not considerably improve the infiltration rate compare to treatment with water in control test. The slight improvement in infiltration rate which was observed in initial irrigation with wetting agents did not continue after the treatment and it was generally the same or less than infiltration rate in sand treated with water in control test.

Results of WDPT on oven-dried and burned sand have been summarized in table 2. These values represent average of 8 WDPT measurements on each sand sample. Degree of sand water repellency have been categorized according to designate table for interpreting water droplet penetration test data in; Bisdom *et al*. (1993); Chenu *et al*. (2000); King (1981) and Throssell (2005).

Initial WDPT showed a slight hydrophobic characteristic in oven-dried sand due to presence of organic matters in sand. Values of standard deviation demonstrated that the variation in WDPT is great despite the close distance between the drops in each sample. The WDPT has reduced considerably (i.e. higher water penetration/lower hydrophobicity) after sand was treated with wetting agents and dried. However, similar reduction in WDPT was observed in sand treated with water. In other word, washing the soil with water or wetting agent solutions reduced the WDPT in a similar manner. The reduction in WDPT could be mainly due to physical washout of the coating hydrophobic materials not the affect of wetting agents.

As expected, WDPT on burned sand before after treatment with wetting agents and water did not indicate considerable change. This implied that, wetting agents had little or no effect on non-repellent sand. The slight change in WDPT in treated burned sand can be due to the change in sand properties caused by soil washout and drying process.

Table 2. Summary of WDPT on oven-dried and burned sand before and after treatment with wetting agents and treatment with water in control test.

Soil type & Wetting agents	**Ave. WDPT Before Treatment Time (S)**	**SD**	**Degree of Water Repellency Before Treatment**	**Ave. WDPT After Treatment Time (S)**	**SD**	**Degree of Water Repellency After Treatment**
Sand. Control	8.6	5.1	1-60 Sec. Slightly Repellent	2.2	1.3	1-60 Sec. Slightly Repellent
Sand. Mineral based	10	3.3	1-60 Sec. Slightly Repellent	0.6	0.2	≤ 1 Sec. Non-Repellent
Sand Humus based	6.8	1.4	1-60 Sec. Slightly Repellent	0.8	0.4	≤ 1 Sec. Non-Repellent
Sand. Surfactant based	9.4	4.2	1-60 Sec. Slightly Repellent	0.7	0.2	≤ 1 Sec. Non-Repellent
B. Sand Control	0.4	0.1	≤ 1 Sec. Non-Repellent	0.5	0.1	≤ 1 Sec. Non-Repellent
B. Sand. Mineral based	0.4	0.1	≤ 1 Sec. Non-Repellent	0.6	0.2	≤ 1 Sec. Non-Repellent
B. Sand. Humus based	0.4	0.1	≤ 1 Sec. Non-Repellent	0.6	0.2	≤ 1 Sec. Non-Repellent
B. Sand. Surfactant based	0.5	0.1	≤ 1 Sec. Non-Repellent	0.6	0.1	≤ 1 Sec. Non-Repellent

4.2 Aquasoil and Wetting Agents

Figure 12, illustrates the result of capillary rise tests on oven-dried Aquasoil using wetting agents and water as rising solution in control test before and after treatment. Solid lines represent the capillary rise of wetting agents in oven-dried Aquasoil and dotted lines represent capillary rise of water in oven-dried Aquasoil treated with wetting agents. Solid and blue dotted lines show the capillary rise in control test.

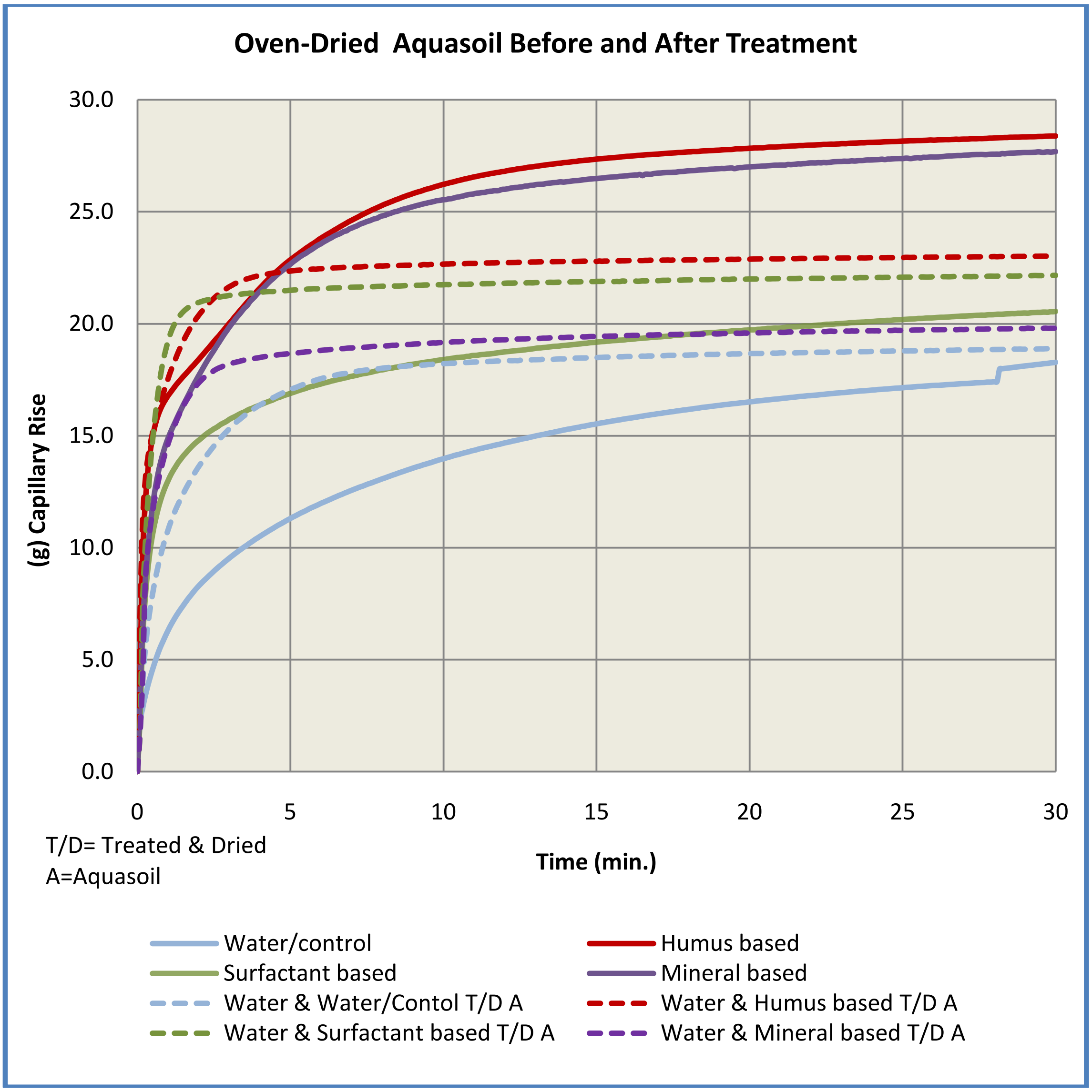

Figure 12. Result of capillary rise of wetting agents and water (control test) in oven-dried Aquasoil and result of capillary rise of water in oven-dried Aquasoil treated with wetting agents and water (control test).

As demonstrated in the figure 12; capillary rise of humus, mineral and surfactant based wetting agents are approximately 47, 45 and 15% higher than capillary rise of water in control test respectively. The significant difference between the capillary rise of water in control test and rise of wetting agents in the soil can be partly due to the effect of organic matters in the soil and the effect of wetting agents in reducing in water surface tension. In other word, these variations can be explained by the way water and each wetting agent's molecules interact with soil hydrophobic components.

Capillary rise of water in soil treated with humus and mineral based wetting agents were reduced approximately by 35 and 45% respectively. This could mean that; the effect of these wetting agents in reducing the water surface tension lasted after treatment and drying process. It also can mean that; these wetting agents contributed to formation of soil hydrophobicity which subsequently resulted in considerable reduction in capillary rise of water into soil.

Conversely, the capillary rise of water in soil treated with water (control test) and soil treated with surfactant based wetting agent increased by 5 and 12% respectively. These relatively slight enhancements in capillary rise of water in treated soil can be due to the change in soil physical properties (washout of hydrophobic coating on soil particles) as a result of treatment and drying process.

The standard deviation of capillary rise tests of water in oven-dried Aquasoil before and after treatment are less than 8.8% and the standard deviation of wetting agents before and after treatment are less than 8%. This indicated minimal variations between the values of the capillary rise for each soil replicate.

Overall, result demonstrated that; capillary rise of water in soil before and after treatment with water remains almost the same. The result also indicated that; capillary rise of water into soil treated with wetting agents has been considerably reduced after treatment. As noted earlier this reduction can be due to formation of hydrophobicity in soil as well as enduring effect of wetting agents in reducing the water surface tension after treatment. However, the difference between the capillary rise of water in soil treated with water in control test is not significantly different to capillary rise of water in treated soil with wetting agents.

Figure 13, illustrates the trend in capillary rise tests in burned Aquasoil before and after treatment with wetting agent and water in control test. Solid lines in the graph represent the capillary rise of wetting agents in burned Aquasoil and dotted lines represent the capillary rise of water in burned Aquasoil treated with wetting agents. Solid and dotted blue lines represent the capillary rise in control test.

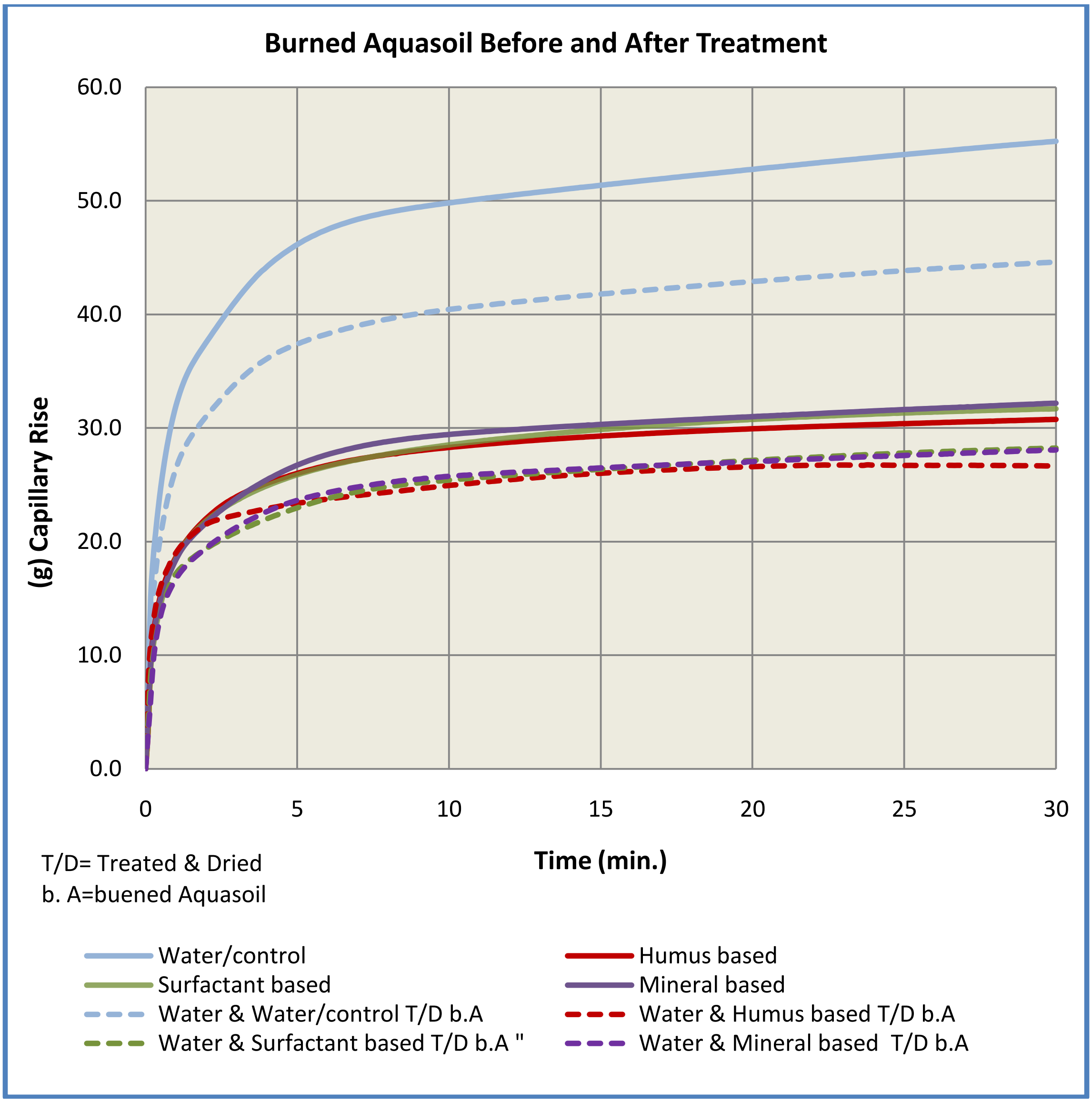

Figure 13. Result of capillary rise of wetting agents and water (control test) in burned Aquasoil and result of capillary rise of water in burned Aquasoil treated with wetting agents and water (control test).

In absence of organic maters in burned Aquasoil, the main factor controlling capillary rise is water surface tension. Therefore, as expected, the capillary rise of water in burned soil was significantly higher than the capillary rise of wetting agents in soil. As illustrated in the figure 13, Capillary rise of water in control test is almost 46% higher than capillary rise of wetting agents in burned soil. This indicated that; wetting agents considerably reduced the water surface tension which results in lower capillary rise in soil compare to capillary rise of water in control test. Result also showed that; average capillary rise of wetting agents in burned Aquasoil are almost the same.

A trend in reduction in capillary rise of water in all treated soils with either wetting agents or water (control test) was observed. However, capillary rise of water in burned Aquasoil treated with water was still significantly higher than the capillary rise of water in burned Aquasoil treated with wetting agents. The difference between the capillary rise of water in soil treated with water (control test) was almost 30% higher than capillary rise of water in soil treated with wetting agents.

The graph also showed that; there was a grater reduction in capillary rise of water in treated soil with water (control test) compare to reduction in capillary rise of water in soils treated with wetting agents. In fact the reduction in capillary rise of water in soils treated with wetting agents was less than 7%. These results indicated that; the effect of wetting agents in reducing water surface tension maintained after treatment and drying process. On the other hand the significant decrease in capillary rise of water in soil treated with water (control test) may indicate the formation of soil hydrophobicity resulted from water treatment and drying process.

The standard deviation of capillary rise of water before and after treatment is less than 5% and the standard deviation of wetting agents in burned Aquasoil before and after treatment are less than 8%. This indicated minimal variations between the values of the capillary rise for each soil replicate.

Overall, results indicated that; all wetting agents have reduced water surface tension and subsequently reduced capillary rise compare to capillary rise of water in control test. Result also showed that; the effect of wetting agents in reducing water surface tension was maintained after treatment and drying process. However, reductions in capillary rise of water in all treated soils indicated the formation of soil hydrophobicity caused by soil washout and and drying process.

Results of infiltration tests on Aquasoil, before and after treatment with wetting agents and treatment with water in control test are converted to meter/day and summarised in figure 14. Data are normalized so that comparison can be made with initial irrigation of water into all soil replicates.

As demonstrated in the graph, application of humus and surfactant based wetting agents did not seem to improve infiltration rate of Aquasoil compare to initial infiltration rate of water in all soils and in control test. In fact, infiltration rate of surfactant based wetting agent was 20% lower than the infiltration rate of water into soil in both initial and second irrigation of water in control test. However, infiltration rate of mineral based wetting agent was almost 18% higher than the infiltration rate of water in soil in control test as well as the initial infiltration rate of water.

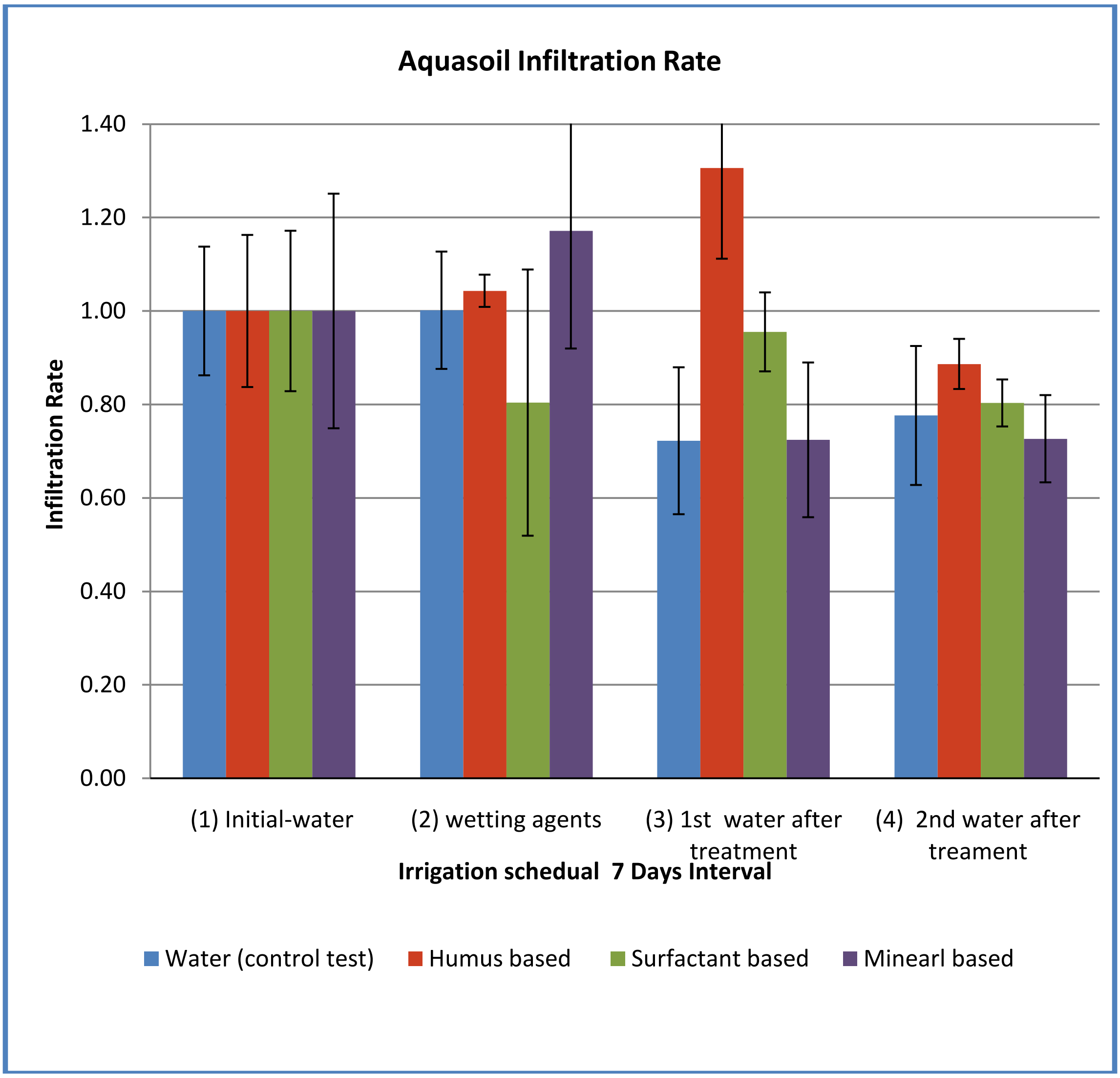

Figure 14. Infiltration rate of wetting agents; humus based, surfactant based and mineral based and water in control test in Aquasoil. (1) initial irrigation with water on all sand barrels, (2) application of wetting agents and water in control test, (3) first irrigation after treatment, using water in all sand barrels (4) second irrigation after treatment, using water on all soil barrels.

Infiltration rate of water after soil were treated with water reduced by almost 30%. The infiltration rate of water into soil treated with surfactant and mineral based wetting agents also did not indicated considerable improvement, however, about 17% enhancement in water infiltration rate into soil treated with surfactant based wetting agent was observed in compare to infiltration rate of surfactant based wetting agent at the time of treatment. Similarly, the infiltration rate of water into soil treated with surfactant based wetting agent was 20% higher than the infiltration rate of water into soil treated with water. The improvement in infiltration rate of water into soil treated with humus based wetting agent was always higher than infiltration rate of water in control test in all stages of tests. In fact the infiltration rate of water in soil treated with humus based wetting agent was 45% higher than infiltration rate of water in soil treated with water.

The infiltration rate of water in second infiltration test after treatment were slightly reduced or remained almost the same for all soils. The infiltration rate of water in second irrigation after treatment in control test was increased by almost 7%. The infiltration rate of water in soil treated with mineral based wetting agent was remained almost the same, and second infiltration rate of water after soil treated with surfactant and humus based was reduced by 18 an 42% respectively.

Comparing the results of infiltration rates in all stages of the tests indicated that; initial application of wetting agent did not considerably improve the rate of infiltration. The result also demonstrated that; the effect of wetting agents was short leaved especially as irrigation and drying process continued. Furthermore, except for the humus based wetting agent, there was not a significant difference between the infiltration rate of water into soil in control test and infiltration rate of wetting agents. Results also indicated continued reduction in infiltration rate of water into all soils treated with wetting agents and water (control test) as the soil irrigation and drying process were continued. This can be an indication of formation of soil hydrophobicity partly due to the effect of wetting agent and water in changing the physical properties of water during the soil irrigation and drying process.

Overall, application of wetting agent did not considerably improve the infiltration rate of water into soil particularly as the irrigation continued.

Table 3, contain summary of the WDPT on oven-dried and burned Aquasoil before and after the treatment with wetting agent and water in control test. Oven-dried Aquasoil initially showed slight water repellency but the water repellency has reduced considerably after soils were treated with wetting agents. Similarly, water drop penetration time was also reduced in soil treated with water in control test. This indicated that; washing the soil with water or wetting agent solutions and drying process reduce the WDPT in a similar manner.

WDPT on burned Aquasoil did not indicate soil hydrophobicity. It was mainly due to absence of organic maters in burned soil. WDPT after burned soil treated and dried with wetting agents have only increased slightly, but as the average water penetration time was 6 sec, soil is still considered non-repellent. In other word, there was no indication of formation of hydrophobicity after soil treated with wetting agent and dried. Similarly, WDPT on burned soil before and after treatment with water in control test did not show water repellency or formation of water repellency. However, the standard deviations for both oven-dried and burned Aquasoil before and after treatment with either water or wetting agents were relatively high. This illustrates significant variation in WDPT despite the "homogeneity" of the Aquasoil and the close distance between the drops in each soil replicate (small surface area of each soil sample). The high standard deviation also indicates that; WDPT may not be a reliable and accurate method of assessing the efficiency of wetting gannets and soil water repellency.

Table 3. Summary of WDPT on oven-dried and burned Aquasoil before and after treatment with wetting agents

Soil type & wetting agents	Ave. WDPT Before Treatment Time (S)	SD	Degree of Water Repellency Before Treatment	Ave. WDPT After Treatment Time (S)	SD	Degree of Water Repellency After Treatment
Aquasoil. Control	20.3	5.2	1-60 Sec. Slightly Repellent	1.1	0.5	1-60 Sec. Slightly Repellent
Aquasoil. Mineral based	16.5	4.2	1-60 Sec. Slightly Repellent	1.0	0.4	≤ 1 Sec. Non-Repellent
Aquasoil. Humus based	20.6	3.8	1-60 Sec. Slightly Repellent	0.6	0.1	≤ 1 Sec. Non-Repellent
Aquasoil. Surfactant based	19.9	3.5	1-60 Sec. Slightly Repellent	1.3	0.8	1-60 Sec. Slightly Repellent
B. Aquasoil Control	0.4	0.1	≤ 1 Sec. Non-Repellent	0.6	0.1	≤ 1 Sec. Non-Repellent
B. Aquasoil. Mineral based	0.5	0.1	≤ 1 Sec. Non-Repellent	0.6	0.1	≤ 1 Sec. Non-Repellent
B. Aquasoil. Humus based	0.5	0.2	≤ 1 Sec. Non-Repellent	0.6	0.2	≤ 1 Sec. Non-Repellent
B. Aquasoil. Surfactant based	0.6	0.1	≤ 1 Sec. Non-Repellent	0.6	0.1	≤ 1 Sec. Non-Repellent

4.3 Landmix and Wetting Agents

Figure 15; illustrate the trend in capillary rise of wetting agents and water in oven-dried Landmix before and after treatment. Solid lines represent the capillary rise of wetting agents in oven-dried Landmix and dotted lines represent the capillary rise of water in soil treated with wetting agents. Solid and dotted blue line represents the capillary rise of water before and after treatment in control test.

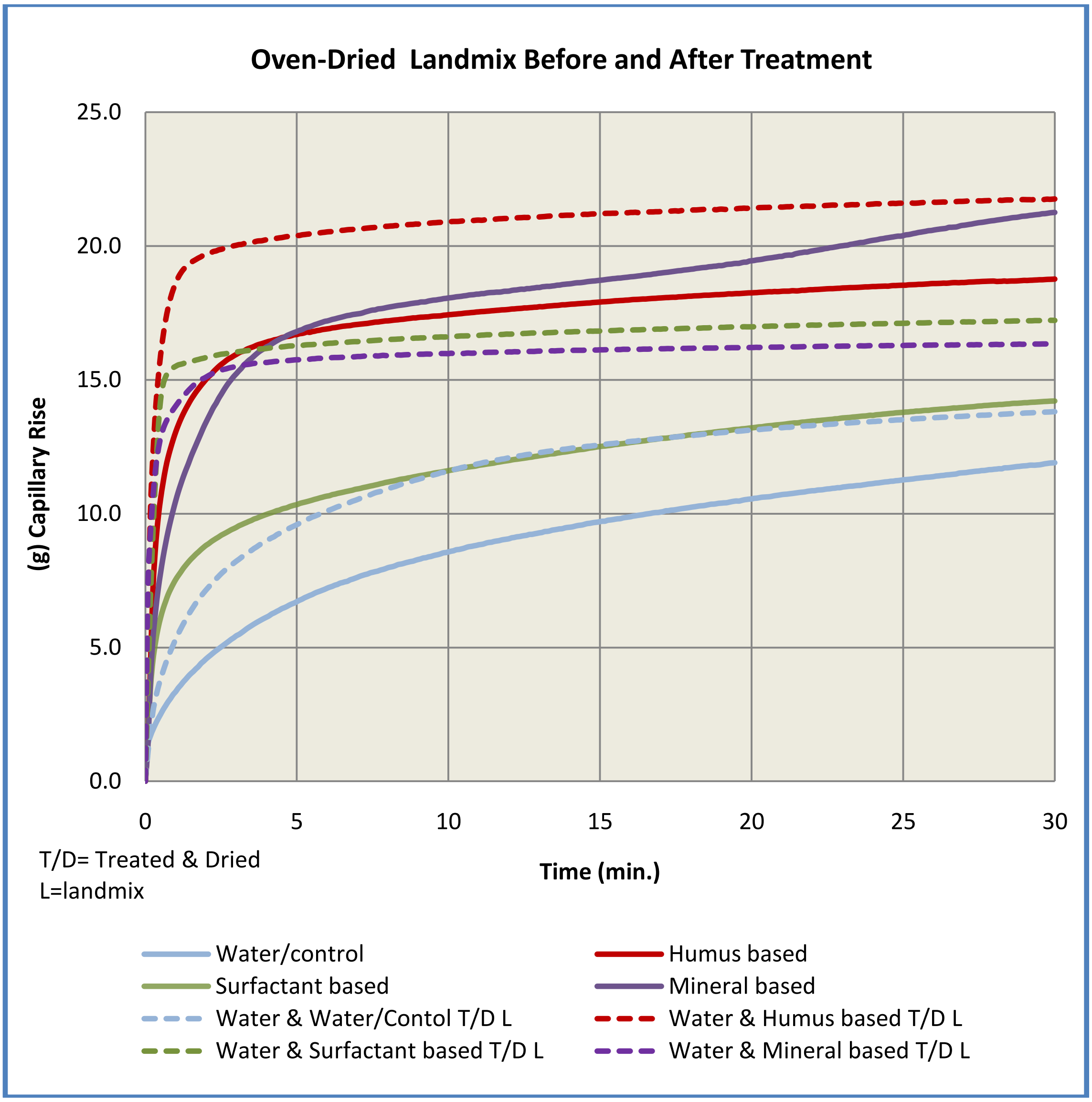

Figure 15. Result of capillary rise of wetting agents and water (control test) in oven-dried Landmix and result of capillary rise of water in oven-dried Landmix treated with wetting agents and water (control test).

As shown in the graph, capillary rise of mineral, humus and surfactant based wetting agents are; 42, 28 and 10% higher than capillary rise of water in soil respectively. Lower capillary rise of water in soil can be due to presence of organic maters and hydrophobic materials coating soil grains which cause soil water repellency and subsequent reduction in capillary rise. On the other hand, higher capillary rise of wetting agents illustrated the affect of wetting agents in reducing water surface tension and overcoming soil hydrophobicity to some degree.

Capillary rise of water in both soil treated with humus and surfactant based wetting agents and soil treated with water have increased by 16, 14 and 10% respectively. The increase in capillary rise of water were observed in both control test and soil treated with wetting agents. Thus, it can be assumed that; soil washout and drying process may have changed the soil properties and contributed in reducing soil water repellency and subsequent increase in capillary rise. In other word, soil washout with either water or wetting agents (surfactant and humus based) and drying process may have decrease the soil hydrophobicity to some extent. However, the degree of increase in capillary rise of water in soils treated with surfactant and humus based wetting agents are at least 5% higher than the increase in capillary rise of water in control test. This indicated that; the increase in capillary rise of water in soil treated with wetting agent may be due to illumination of factors that reducing the water surface tension and changes to soil property resulted from washout and drying process.

In contrast, the capillary rise of water in soil treated with mineral based wetting agent has decreased by almost 24% compare to initial capillary rise of mineral based wetting agent. This reduction may occur due to formation of hydrophobicity caused by treatment with wetting agent and drying process.

The standard deviation of capillary rise of water before and after treatment is less than 5% and the standard deviation of wetting agents in burned landmix before and after treatment are less than 10%. This indicated that; the minimal variations between the values of the capillary rise for each set of soil replicates.

The overall result of capillary rise in oven-dried Landmix before and after treatment indicated that; soil hydrophobic characteristic was altered as a result of initial capillary test with water and wetting agents as well as drying process.

Results of capillary rise of wetting agents and water (control test) in burned landmix, before and after treatment are illustrated in figure 16. The solid lines represent the capillary rise of wetting agents and dotted lines show capillary rise of water in treated soil. Solid and dotted blue lines represent the capillary rise of water before and after treatment in control tests.

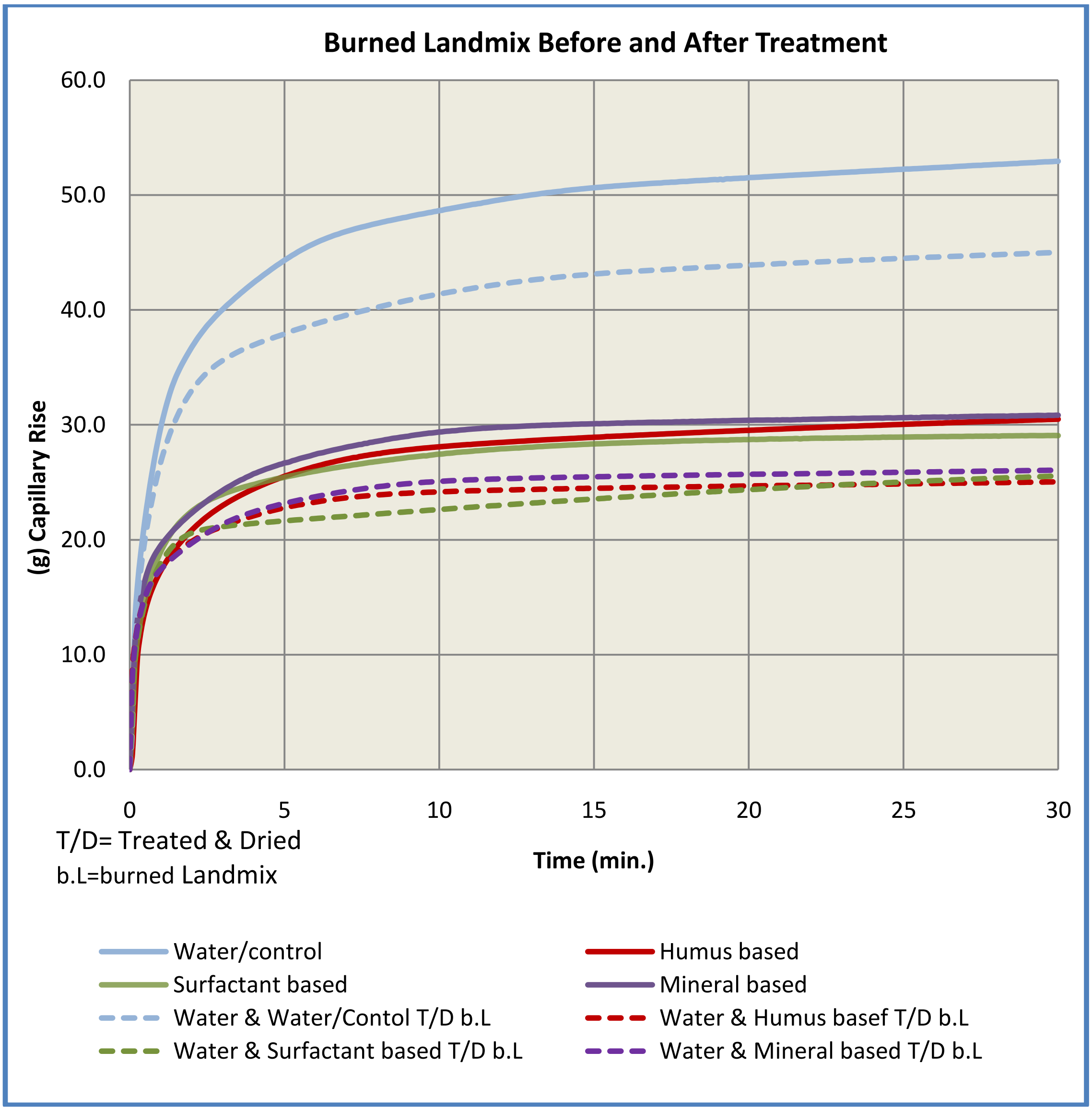

Figure 16. Result of capillary rise of wetting agents and water (control test) in burned Landmix and result of capillary rise of water in burned Landmix treated with wetting agents and water (control test).

When organic matters eliminated from soil, the main contributing factor effecting capillary rise is water surface tension. Therefore, as expected, the capillary rise of water in burned soil is considerably higher than capillary rise of wetting agents. This is because wetting agents reduce water surface tension and subsequently reduce the capillary rise in soil. As illustrated in the graph, capillary rise of surfactant, humus and mineral based wetting agents are; 41, 39 and 38% lower than capillary rise of water in burned Landmix.

Capillary rise of water in burned Landmix treated with water (control test) as well soil treated with mineral, surfactant and humus based wetting agents have decreased by; 14, 8, 6 and 10% respectively. Reduction in capillary rise of water in all treated soils can be the result of formation of soil hydrophobicity due to soil washout and drying process not solely the affect of wetting agents in reducing the water surface tension. However, as illustrated in the graph, decrease in capillary rise of water in soil treated with water (control test) on average is 8% more than the reduction in capillary rise of water in soil treated with wetting agents. This indicated that, either the effect of wetting agents in reducing water surface tension was maintained after soil was treated and dried and or treatment with wetting agents has contributed to formation of soil hydrophobicity but slightly less than the soil treated with water in control test.

The standard deviations of capillary rise of water before and after treatment are; 4 and 13% respectively and the standard deviation of wetting agents in burned landmix before and after treatment are less than 10%. This indicated minimal variations between the values of the capillary rise for each set of soil replicates.

Overall, wetting agents may have been effective in reducing the water surface tension before and after the treatment. However, soil treatment with either wetting agents or water and drying process have contributed to formation of soil hydrophobicity and subsequent reduction in capillary rise of water in all treated soils.

Result of WDPT on oven-dried and burned Landmix, before and after treatment with wetting agents and water (control test) has been summarized in table 4. WDPT on oven-dried Landmix indicated a slight water repellencey. WDPT showed a significant reduction in water drop penetration time into soil after soil was washed with wetting agent and dried in oven. Similar reduction in water drop penetration time was observed in control test. This indicated that, reduction in WDPT or soil hydrophobic characteristic is mainly due to changes in soil properties during the soil treatment (saturation of soil with wetting agent or water) and drying process. The relatively high standard deviation in WDPT before and after soil treatment indicated the large variation in soil water repellency in small area of the soil samples.

WDPT on burned Landmix showed no sign of soil water repellency, demonstrating the contribution of soil organic matters in water repellency. WDPT on treated and dried burned Landmix also did not indicate any changes in degree of soil hydrophobicity. This could mean that wetting agents had little or no affect in altering soil hydrophobicity. Similar to oven-dried Landmix, the standard deviation of WDPT in burned Landmix before and after treatment was relatively high. This demonstrated the relatively high variation of soil hydrophobicity in close proximately of small soil samples.

Table 4. Summary of WDPT on oven-dried and burned Landmix before and after treatment with wetting agents and treatment with water in control test.

Soil types & wetting agents **B=Burned**	**Ave. WDPT Before Treatment Time (S)**	**SD**	**Degree of Water Repellency Before Treatment**	**Ave. WDPT After Treatment Time (S)**	**SD**	**Degree of Water Repellency After Treatment**
Landmix. Control	37.1	7.9	1-60 Sec. Slightly Repellent	9.4	2.9	1-60 Sec. Slightly Repellent
Landmix. Mineral based	50.5	9.4	1-60 Sec. Slightly Repellent	1.1	0.5	1-60 Sec. Slightly Repellent
Landmix. Humus based	52.6	7.8	1-60 Sec. Slightly Repellent	0.6	0.1	≤ 1 Sec. Non-Repellent
Landmix. Surfactant based	38.0	12.9	1-60 Sec. Slightly Repellent	0.5	0.1	≤ 1 Sec. Non-Repellent
B. Landmix. Control	0.4	0.1	≤ 1 Sec. Non-Repellent	0.4	0.1	≤ 1 Sec. Non-Repellent
B. Landmix. Mineral based	0.5	0.1	≤ 1 Sec. Non-Repellent	0.6	0.1	≤ 1 Sec. Non-Repellent
B. Landmix Humus based	0.6	0.2	≤ 1 Sec. Non-Repellent	0.6	0.2	≤ 1 Sec. Non-Repellent
B. Landmix. Surfactant based	0.5	0.1	≤ 1 Sec. Non-Repellent	0.5	0.1	≤ 1 Sec. Non-Repellent

Figure 17; illustrate the Infiltration rates of water and wetting agents in Landmix during all stages of the trial.

As shown in the graph, the average rate of water infiltration into soil (control test) continuously was higher compare to the infiltration rate of wetting agents into soil in all stages of infiltration test. The average infiltration rate of each wetting agent during the course of trial was considerably varied. However, a trend in reduction of infiltration rate for both wetting agents and water was clearly observed as irrigation continued.

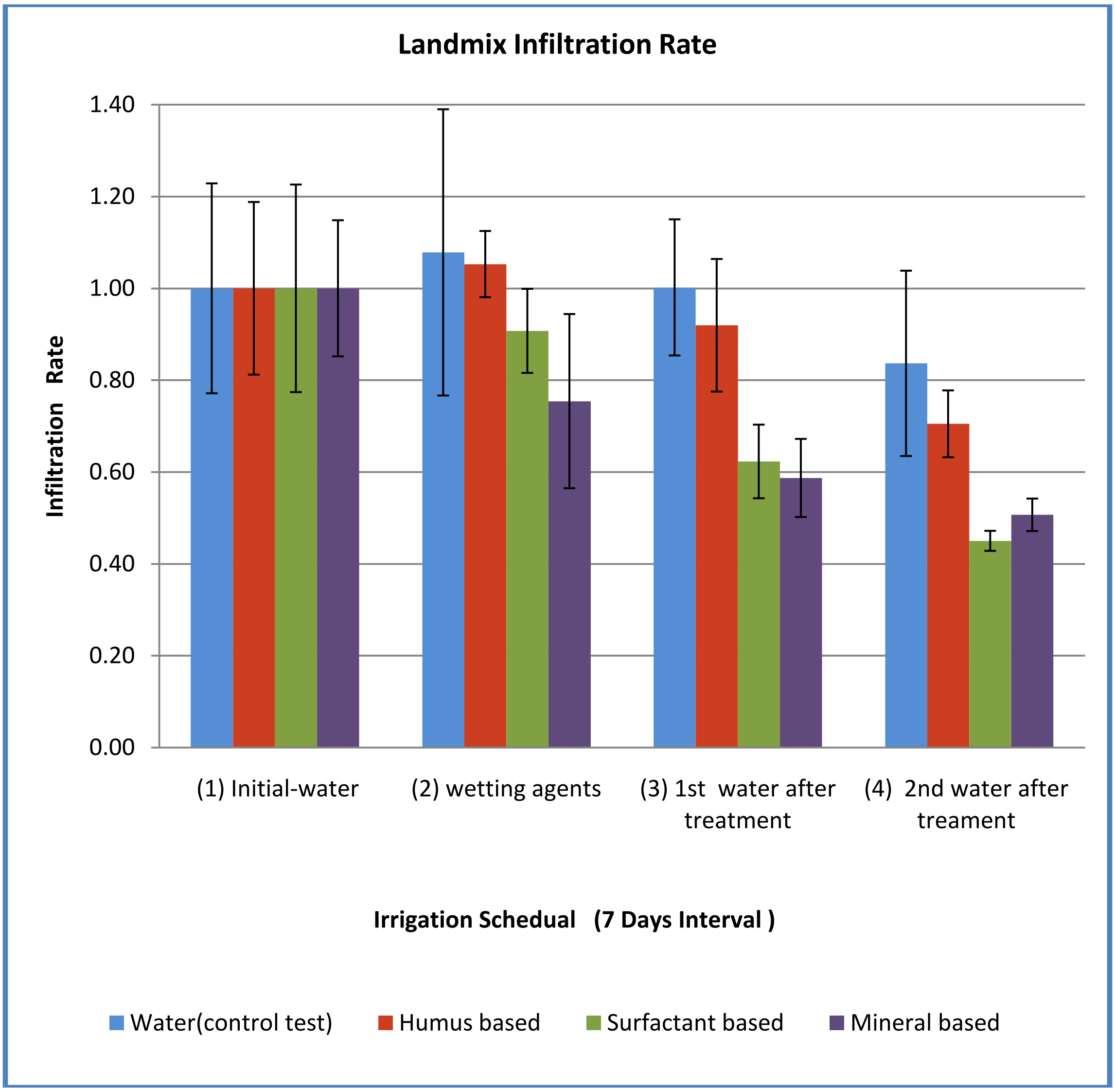

Figure 17. Infiltration rate of wetting agents; humus based, surfactant based and mineral based and water in control test in Landmix. (1) initial irrigation with water on all sand barrels, (2) application of wetting agents and water in control test, (3) first irrigation after treatment, using water in all sand barrels (4) second irrigation after treatment, using water on all soil barrels.

As demonstrated in the graph, the infiltration rate of water into soil was at least 4, 17 and 30% higher than infiltration rate of humus, surfactant and mineral based wetting agents respectively. Similarly, the infiltration rate of water into soil in the first irrigation after the treatment was higher than infiltration rate of water into soil treated with wetting agents. The infiltration rate of water into soil in first irrigation after treatment was 8, 38 and 42% higher than infiltration rate of water into soils treated with humus, surfactant and mineral based wetting agents respectively. Similar trend continued in the second irrigation after the treatment. The infiltration rate of water in control test in second irrigation after the treatment was 11, 41 and 30% higher than the infiltration rate of water into soil treated with humus, surfactant and mineral based wetting agent respectively.

There was a relatively higher standard deviation in average infiltration rate of water was observed in all stages of control test. This high standard deviation represented the considerable variation in soil hydrophobicity in each soil barrels. However, despite this relatively high standard deviation for control test, the infiltration rate of wetting agents into soil at the time of application and infiltration rate of water into soil treated with wetting agents are still lower than infiltration rate of water in control test.

As noted earlier, a trend in reduction of infiltration rate of water into soil was observed as irrigation continued for both control test and soils treated with wetting agents. This gradual reduction in infiltration rate in first and second irrigation after treatment could be due to the changes in soil physical properties and increase in soil hydrophobicity as a result of treatment and drying process. However, the infiltration rate of water in control test in all stages of trial was still higher than the infiltration rate of wetting agents into soil and infiltration rate of water in soil treated with wetting agents in first and second irrigation after treatment. These results indicated that; application of wetting agents not only did not enhance the infiltration rate of water into soil while and after the application, but also it reduced the infiltration rate of water after soil was treated and dried. Results also indicted that; the application of wetting agents may in fact have adverse effect and caused soil to become more water repellent compare to treatment with water and drying process.

4.4 Comparing Efficiency of Wetting Agents in Various Soils

The initial infiltration rate with water has been used as reference for comparing the changes in infiltration rate during and after soil treated with a wetting agent.

4.4.1 Humus Based Wetting Agent and Soils

Figure 18; demonstrates the performance of humus based wetting agent on Sand, Landmix and Aquasoil before and after treatment.

Application of humus based wetting agent has only increased infiltration rate in landmix and Aquasoil slightly. In first irrigation with water after treatment, infiltration rate in Aquasoil was increased by approximately 25% and a reduction in infiltration rate was recorded for others soils. Second infiltration rate after treatment also did not show any improvement in rate of infiltration. Overall, application of humus based wetting agent seemed to only improve infiltration rate in Aquasoil mainly after treatment. It did not enhance the infiltration rate of other soils.

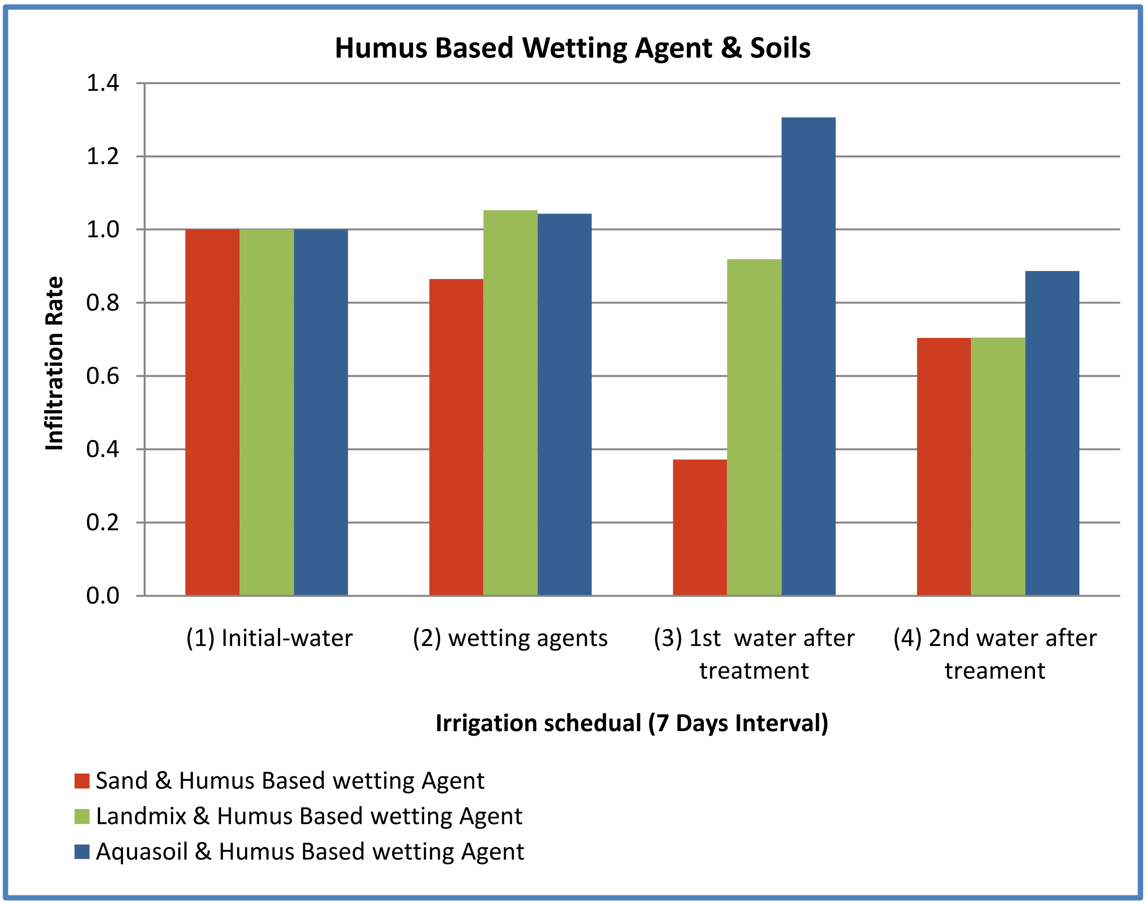

Figure 18. Infiltration rate of Humus based wetting agent on Sand, Landmix and Aquasoil before and after treatment.

4.4.2 Surfactant Based Wetting Agent and Soils

Figure 19; illustrates the result of infiltration rate of surfactant based wetting agent on Sand, Landmix and Aquasoil before and after treatment. During the application of surfactant based wetting agent, the infiltration rate in sand was increased by approximately 10% compare to initial infiltration with water. Conversely, infiltration rate in Landmix and Aquasoil were deceased by 10 and 20% respectively. In first infiltration after the treatment infiltration rate has decreased for all soils in comparison to the initial infiltration rate. However, there was a slight increase in infiltration rate in Aquasoil in first irrigation after treatment.

In second irrigation after treatment, a slight increase in infiltration rate in sand was observed but the infiltration rate in Aquasoil was decreased. There was a continued decrease in infiltration rate of surfactant based wetting agent on Landmix during and after treatment was observed. Overall, surfactant based wetting agent was only slightly effective on sand mainly during the application and in second irrigation after treatment. Application of surfactant based wetting agent on Landmix and Aquasoil not only did not improve the infiltration rate but also it had an inverse affect.

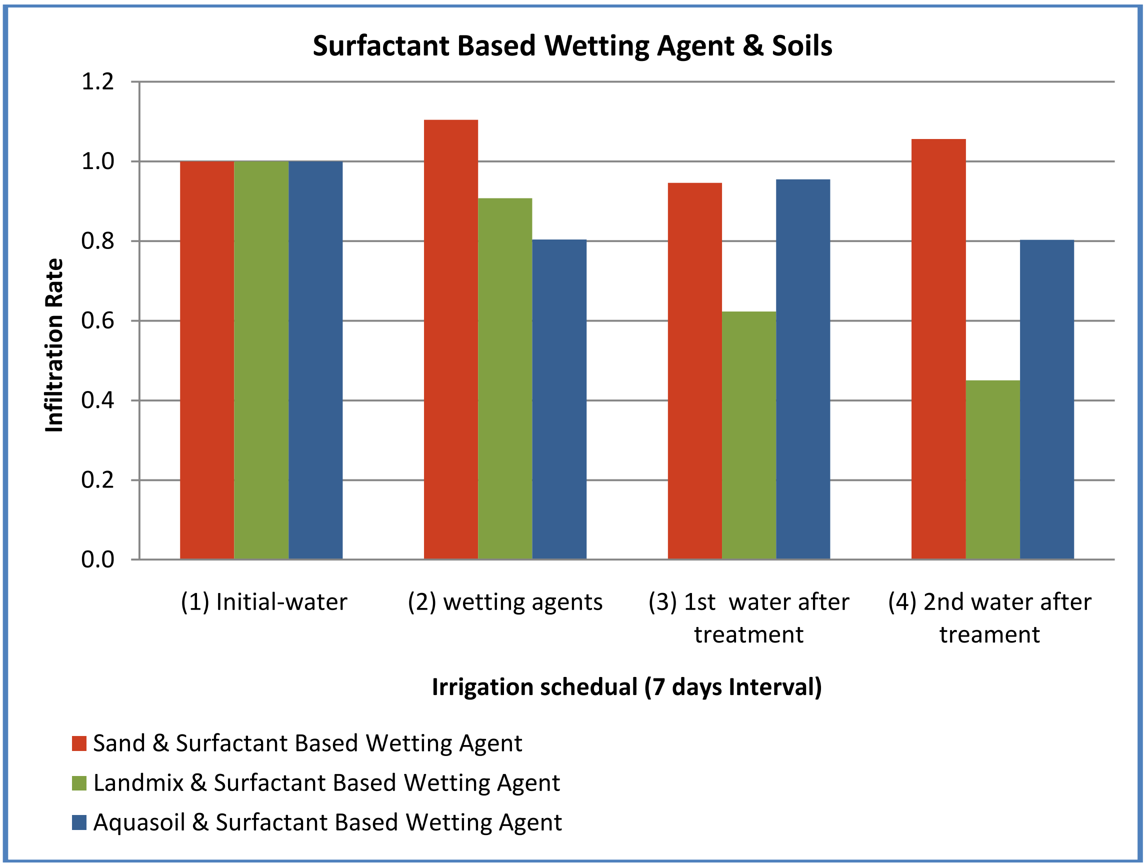

Figure 19. Infiltration rate of Surfactant based wetting agent on Sand, Landmix and Aquasoil before and after treatment.

4.4.3 Mineral Based Wetting Agent and Soils

Result of Infiltration rate of mineral based wetting agent on sand, Landmix and Aquasoil before and after treatment is illustrated in figure 20. Application of mineral based wetting agent has increased infiltration rate in Aquasoil by approximately 18% and by 2% in sand. A reduction of approximately 22% in infiltration rate was recorded for Landmix. The infiltration rate in first and second irrigation after treatment did not indicate any improvement in infiltration rate for any of the soils compare to initial irrigation with water.

The infiltration rate in Landmix showed a continuous reduction during and after the application of mineral based wetting agent. There was also a variation in reduction of infiltration rate in first and second irrigation after treatment for both Sand and Aquasoil. In general, application of mineral based wetting agent on all soils did not indicate a considerable improvement in soil wettability during and after the treatment.

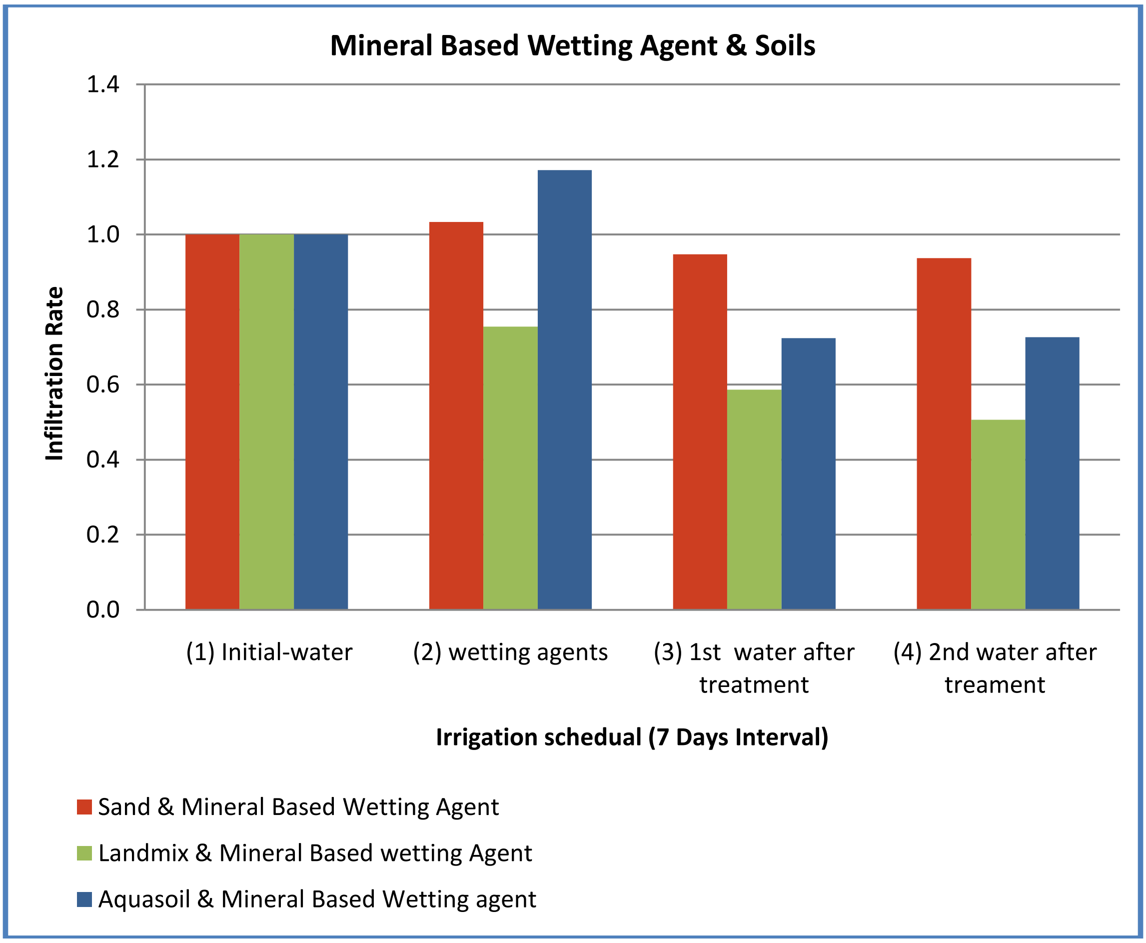

Figure 20. Infiltration rate of Mineral Based wetting agent on Sand, Landmix and Aquasoil before and after treatment.

4.5 Summary of Findings

- The capillary rise of the wetting agent solution was mainly affected by the solution surface tension and not by the organic matter content in the soil.

- The capillary rise in burned soils particularly for water as rising solution is higher than in oven-dried soil, demonstrating the contribution of organic matters in soil hydrophobicity.

- Generally, there was a reduction in capillary rise in both burned and oven-dried soils after soils were treated and dried compare to initial capillary rise with either water or wetting agents.

- There seemed to be a greater drop in the capillary rise in soils treated with wetting agents (after soil was dried) as compared to the decrease in capillary rise in the soil treated with water.

- The variation in capillary rise of different wetting agents on each soil is due to interaction of each wetting agent molecules with soil hydrophobic materials.

- The initial reduction of capillary rise of wetting agent in soil compare to capillary rise of water in soil is mainly due to the affect of wetting agents in reducing the water surface tension. But the continued reduction in capillary rise in soil treated with wetting agent would be due to formation of soil hydrophobicity. However, this only imply if the decrease in capillary rise in soil treated with wetting agent is higher than the decrease in capillary rise in soil treated with water.

- Presence of organic matters enhanced soil WDPT, yet washing the soil with water or wetting agent solutions reduced the WDPT in a similar manner.

- WDPT on burnet soil (no organic matter) did not show any repellencey and no change occurred after soil washed/mixed with water or wetting agent solutions. In other word, neither water nor wetting agent treatment had any effect on altering water repellency in burned soil.

- Variation in WDPT is significant despite the “homogeneity” of the sand and the close distance between the drops (few cm from each other) in small area of the soil samples. The same phenomena appeared in all soils before and after soils were treated with wetting agents.

- WDPT does not seem to be a very effective / reliable method of evaluating soil water repellency and efficiency of wetting agents.

- There is a development of water repellency in the water treatment over time through wetting and drying process.

- Similar trends in developing soil water repellency and usually to greater extent are found in treatment with wetting agents. However, there is exception which is usually different from soil to soil.

- Sometimes when the wetting agents are used the infiltration rate increased but this has changed over time after soil dried and irrigated again.

- No pattern with regard to the wetting agents could have been found. Each wetting agent behaved differently in each soil.

- Generally, the application of wetting agents in this trial did not seem to effectively enhance wettability of selected soils.

5 Conclusion

In conclusion, it was observed that initial application wetting agents moderately enhanced soil wettability. This was likely due to the affect of wetting agent solutions in reducing water surface tension. Nevertheless, the improved soil wettability was often temporally and even in some cases the wettability were reduced after treated soil was dried and irrigated with water. Similar trend was also observed in capillary rise of wetting agent solution in soil columns and WDPT. These observations lead to the hypothesis that; surfactant molecules in the wetting agents bond to soil particles in the same way as organic hydrophobic materials that coat the soil grains.

Findings in this trail indicated that; application of selected wetting agents not only did not result in enduring improvement in soil wettability, but also in some cases appear to enhance soil water repellency. However, it cannot be said with certainty that, the application of wetting agents subject to this study would have the same outcome in other soil types and conditions. To substantiate the results, further investigation required to understand the mechanism by which wetting agent molecules interact with soil particles.

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